

The Impact of Dredged Holes on Oxygen Demand in the Lower Bay, New York Harbor

S. M. Swartz

B. H. Brinkhuis

**CIRCULATING COPY
Sea Grant Depository**



SPECIAL REPORT 17



REFERENCE 78-5

MARINE SCIENCES RESEARCH CENTER
STATE UNIVERSITY OF NEW YORK
STONY BROOK, NEW YORK 11794

THE IMPACT OF DREDGED HOLES ON OXYGEN DEMAND
IN THE LOWER BAY, NEW YORK HARBOR

by

Scott M. Swartz

and

Boudewijn H. Brinkhuis

December 1978

*Sponsored by the New York Sea Grant Institute
through a contract with the New York State
Office of General Services, and by SUNY.*

Special Report 17

Reference 78-5

Approved for Distribution

J. R. Schubel

J. R. Schubel, Director

Abstract

The Impact of Dredged Holes on Oxygen Demand in the Lower Bay, New York Harbor

The purpose of this investigation was to determine the effects, if any, of dredged holes in the seabed of the Lower Bay of New York Harbor on oxygen dynamics in the water column and surficial sediments. The data for this study were collected during five cruises in the Lower Bay between February, 1978 and August, 1978. Samples of surficial sediments were analyzed for organic carbon, acid-soluble sulfide, and oxygen consumption rate. In addition, the water column at many of the stations was sampled at various depths to profile temperature, salinity, and dissolved oxygen.

The results show that the presence of dredged holes affects oxygen demand of the sediments and oxygen concentrations of the overlying waters. These effects are variable, and dependent on the location of the dredged holes. Lower oxygen concentrations were generally found in dredged holes on the West Bank. There was no effect of dredged holes on oxygen dynamics on the East Bank. This difference is ascribed to hydrodynamic dissimilarities between the East and West Banks, and the accumulation of fine organic matter only on the West Bank.

Table of Contents

	<u>Page</u>
Abstract.....	ii
Table of Contents.....	iii
List of Figures.....	v
Acknowledgements.....	vii
Introduction.....	1
Materials and Methods.....	4
Description of study area.....	4
Sampling strategy.....	9
Sampling procedures and laboratory analyses.....	10
1. Organic carbon.....	11
2. Sulfide.....	11
3. Oxygen consumption rate.....	14
4. Temperature and dissolved oxygen profiles.....	15
5. Salinity.....	18
Results.....	20
Sulfide and organic content of sediments.....	20
Oxygen concentration of the bottom water.....	25
Oxygen percent saturation of the bottom water.....	29
Vertical profiles of oxygen concentration and Sigma-T.....	48
Summary of results.....	57

Table of Contents

	<u>Page</u>
Discussion.....	63
Conclusions.....	70
References.....	71
Appendix A.....	73
Appendix B.....	76

List of Figures

<u>Figure</u>	<u>Page</u>
1 Map of Lower Bay Complex and the study area within the Lower Bay.....	5
2 Map of study area, showing location of sampling stations.....	7
3 Photograph of sediment core in continuous-flow water bath.....	16
4 Relationship between organic carbon and sulfide.....	21
5 Efficiency regression line of sulfide analysis.....	24
6 Relationship between temperature and dissolved oxygen concentration.....	27
7 Relationship between temperature and oxygen percent saturation.....	31
8 Relationship between organic carbon and oxygen percent saturation.....	34
9 Relationship between sulfide and oxygen percent saturation.....	38
10 Relationship between temperature and total oxygen consumption rate.....	41
11 Relationship between organic carbon and total oxygen consumption rate.....	43
12 Relationship between sulfide and chemical oxygen demand.....	46

List of Figures

<u>Figure</u>	<u>Page</u>
13 Relationship between total oxygen consumption rate and oxygen percent saturation.....	49
14 Relationship between chemical oxygen demand and oxygen percent saturation.....	51
15 Vertical profile of dissolved oxygen concentration versus depth in May.....	53
16 Vertical profile of dissolved oxygen concentration versus depth in June.....	55
17 Vertical profile of Sigma-T versus depth in June.....	58
18 Vertical profile of Sigma-T versus depth in August.....	60

Acknowledgements

We are indebted to Chris Stuebe, Captain of the R/V ONRUST, for his expert assistance on the many sampling cruises conducted during the course of this investigation, and to Clifford Jones for his help on the cruises and in the laboratory. We wish to thank Hirlsa White for the final typing of this manuscript.

This research was supported by research grants #431-T102D and #431-T112D to Boudewijn H. Brinkhuis from the New York State Office of General Services. This study was conducted as part of an M.S. thesis by Scott M. Swartz submitted to the Marine Sciences Research Center of the State University of New York at Stony Brook.

Introduction

Sand deposits in the Lower Bay of New York Harbor have been the largest single source of commercial sand for fill and construction in the New York metropolitan area since 1963 (Schlee, 1975). According to the New York State Office of General Services (Marotta, personal communication), more than 95 million cubic yards of sand have been mined from the Lower Bay between the years of 1950 and 1973. This sand has been used for such construction projects as the Battery Park City, Ports Newark and Elizabeth, portions of the New Jersey Turnpike, and the Newark Airport extension.

Demand for sand obtained from the Lower Bay will likely increase in the future. Based on current and pending construction proposals, the demand for sand in the New York metropolitan area for the next several years will probably exceed 8.5 million cubic yards per year (Schlee, 1975). Sand resources located on land in or near to the New York metropolitan area have dwindled, due either to depletion or competition for land area with urban and suburban spreading. The value of real estate is currently too high to allow commercial sand and gravel mining companies to realize a profit from exploitation of inland deposits in the metropolitan area. Further, overland transport of sand and gravel from areas greater than 50 or 60 miles away from utilization sites is becoming prohibitively expensive. Thus it appears that in the future, when

large quantities of sand are needed for major construction projects in the New York metropolitan area, such as the proposed West Side Expressway, it will be more economical and efficient to dredge and barge sand from the Lower Bay than to mine it from inland deposits.

Before large scale commercial sand mining from the Lower Bay is permitted, the New York State Department of Environmental Conservation and the U.S. Environmental Protection Agency have deemed it necessary to determine the environmental impacts of sand mining operations in the Lower Bay. As a result, three areas of concentrated research in the Lower Bay were initiated by researchers from the Marine Sciences Research Center at Stony Brook, New York in 1977. These include 1) determining the extent and renewal rate of sand resources, 2) assessing the biological effects of sand mining, and 3) evaluating the effects of sand mining on shore erosion.

Preliminary results of the biological study indicated that several holes created in the seabed of the Lower Bay, as a result of sand mining operations, have been filling in with very fine silt (particles between 4 and 8 μm in diameter), having a high organic matter content. From an examination of sediment cores, Brinkhuis (unpublished data) estimated a sedimentation rate of approximately 10 cm per year. The relatively rapid accumulation of organic matter on the seabed within these dredged holes might increase the oxygen consumption rate of the sediment by the

chemical oxidation of reducing substances (COD) and respiration of organisms, if any, in the sediment.

Further, deep holes isolated in shallow water can cause alterations of the benthic water circulation patterns, such that current velocities and the resultant magnitude of turbulent mixing in the water column are reduced (Wilson, personal communication). As a result, oxygen rich surface waters might no longer reach sediments at the bottom of the holes, resulting in anaerobic conditions. In a study conducted in Great South Bay, an estuarine system along the south shore of Long Island, New York, Turano (1968) found that dredging of holes in the seabed can induce organic matter accumulations and seabed oxygen consumption rates equal to areas with large scale human utilization. He found that the oxygen consumption rates in such areas are capable of producing anaerobic conditions in the overlying waters during the summer months.

The findings of Turano, and the preliminary results obtained by Brinkhuis indicating the rapid accumulation of fine grained and organic sediment particles in the bottom of several dredged holes, provided the impetus for this study, whose purpose is assessing the effect of dredged holes in the seabed of the Lower Bay of New York Harbor on the oxygen demand by the surficial sediments.

Materials and Methods

Description of study area

The Lower Bay of New York Harbor is part of an estuarine area known as the Lower Bay Complex, whose physical characteristics and oceanography have been described in detail by Duedall et al. (1976). It includes Raritan, Lower, and Sandy Hook Bays, and is at the mouths of the Hudson and Raritan Rivers (see Fig. 1).

Waters of the Lower Bay Complex exchange and mix with 1) the waters of the Upper Bay of New York Harbor through a narrow constriction between Brooklyn, and Staten Island, called the "Narrows", and 2) the sea through a relatively wide (~ 8 km) transverse opening between Sandy Hook, New Jersey and Rockaway Point, New York (referred to as "the Sandy Hook-Rockaway Point transect" in the remainder of this paper).

The Lower Bay Complex is shallow (5-20 m), but has an irregular submarine topography composed of numerous shoals, banks, and ship channels. These features, shown in Fig. 2, have been described in detail by Fray (1969). Within the Lower Bay there are several extensive shoal areas which rise above the general level of the bottom, and numerous areas which have been dredged significantly below the general level of the bottom.

On the West Bank of Ambrose Channel (see Fig. 2) there are three areas which were dredged for sand prior to 1973. One relatively small hole (Area "A"), approximately 0.35 km^2 in area

Figure 1

Map of the Lower Bay Complex, showing the location of Raritan, Lower, and Sandy Hook Bay, and the study area within the Lower Bay.

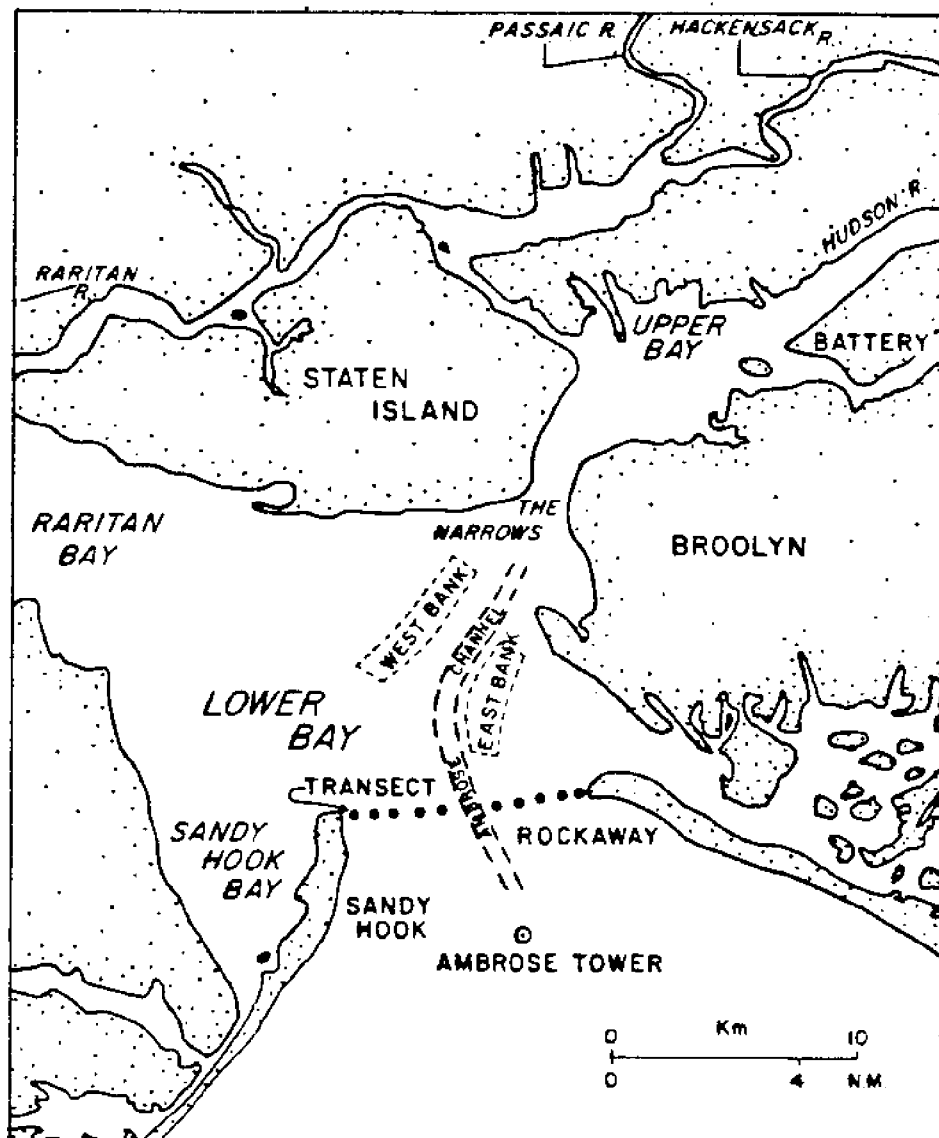


Figure 2

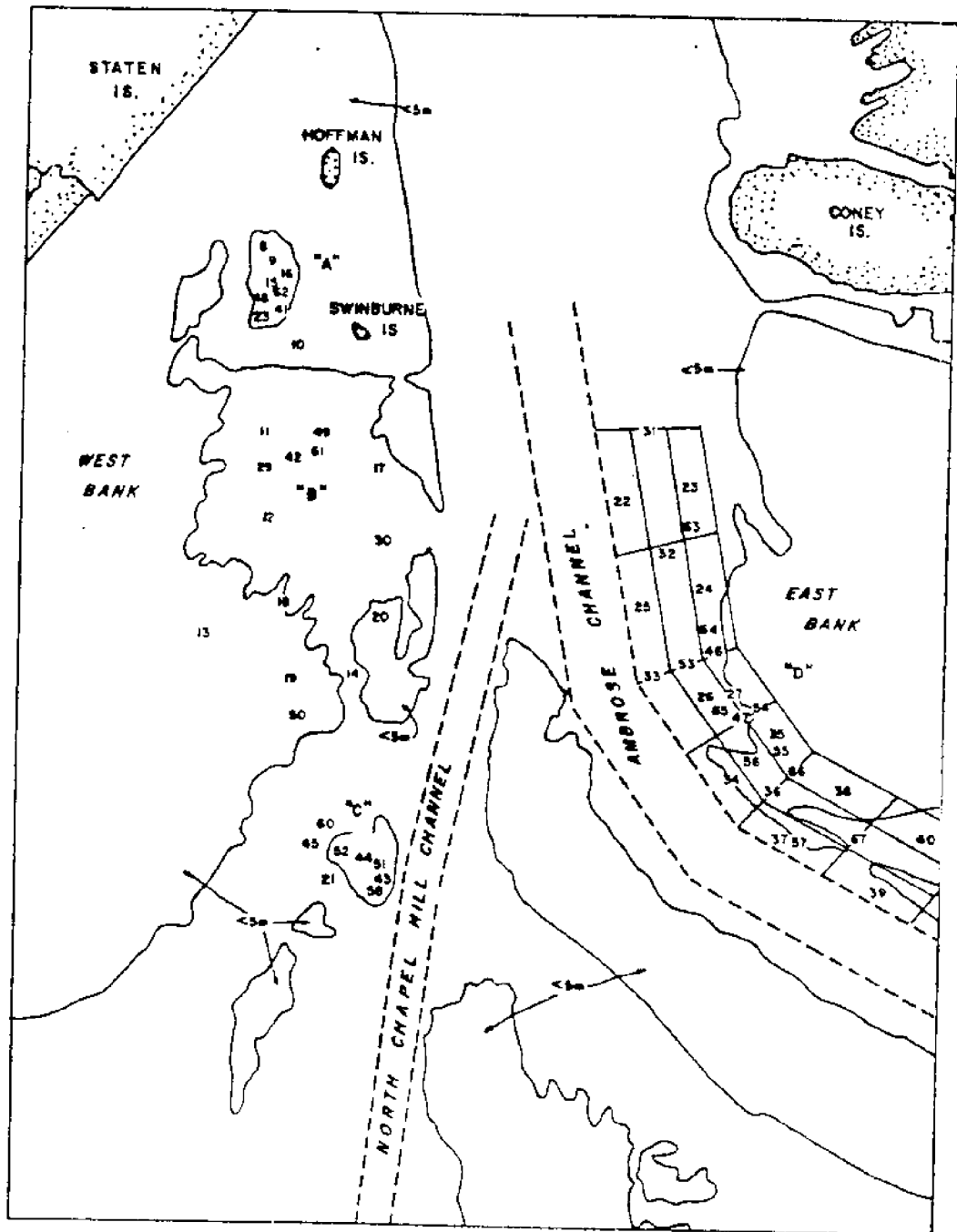
Map of the study area, showing the location of the sampling stations (denoted by number), and the dredged areas (denoted by letter).

Area "A" --- Dredged hole, 0.35 km² and 8-11 m deep.

Area "B" --- Dredged hole, 3.50 km² and 8-14 m deep.

Area "C" --- Dredged hole, 0.33 km² and 20 m deep.

Area "D" --- Large shoal, 2-4 m deep, with numerous natural channels and deep holes dredged between 1973 and 1976.



and 8-11 m deep, is located just west of Swinburne Island. A larger hole (Area "B"), approximately 3.5 km² in area and 8-14 m deep, is located just south of the smaller hole. The third hole (Area "C"), slightly smaller than the first and 20 m deep, is located south of the large hole, and west of the North Chapel Hill Channel.

On the East Bank of Ambrose Channel there is a large shoal (Area "D") which rises within 2-4 m of the surface. There are numerous irregularly shaped holes 18-22 m deep which resulted from dredging for sand between 1973 and 1976. Most of the dredged areas on the East Bank are connected to the deeper waters of Ambrose Channel by natural channels resulting from dredging.

Brinkhuis (unpublished data) found the bottom sediments of the study area to be primarily silts in dredged areas on the West Bank, and fine to medium grained sands in dredged areas on the East Bank as well as in undisturbed areas on both the East and West Banks. The major source of surficial sediments found on the East Bank is the westward littoral drift of sand from the south shore of Long Island. The sources of surficial sediments found on the West Bank are the suspended particulate loads from the Hudson, Sandy Hook, and Raritan Rivers, and northward littoral drift of sand from the Sandy Hook peninsula (Kastens et al., 1978).

Sampling strategy

Detailed bathymetry, using an Elac model LAZ-41 depth recorder, was conducted on two preliminary cruises in order to

ascertain where changes in the bottom topography of the Lower Bay had occurred as a result of sand mining operations. The navigation accuracy was approximately 0.02 nautical miles. Changes were detected by comparing these surveys with archived nautical charts. Supplemental data on the date, location, and volume of mining operations conducted since 1950 were obtained from the New York State Office of General Services. Using this information, a sampling strategy was developed such that areas which had been mined could be compared with those that were undisturbed by mining operations. Since holes had been dredged on both the East and West Banks of Ambrose Channel, mined and undisturbed areas were sampled on both the East and West Banks.

Sampling procedures and laboratory analyses

The data for this study were collected during five cruises in the Lower Bay of New York Harbor aboard the R/V Onrust between February, 1978 and August, 1978. Figure 2 shows the location of each sampling station. A single sample of the surficial sediment, to a depth of 10 cm, was obtained at each station using a Hydro-Products Shipek bottom grab and placed in a plastic bag. The samples were analyzed for organic carbon, acid-soluble sulfide, and oxygen consumption rate of the surficial sediments. In addition, the water column at many of the stations were sampled at various depths for measurements of temperature, salinity, and

and dissolved oxygen.

1. Organic carbon

In the laboratory, each sediment sample was thoroughly mixed in its plastic bag and a sub-sample weighing 500 g wet was taken for organic carbon analysis. Percent loss on ignition was used as a measure of organic carbon content, and was determined using methods described by Gross (1972). Briefly, samples were dried in an oven at 65°C until constant weight was reached. Samples were then lightly disaggregated with a mortar and pestle and all particles greater than 2.0 mm in diameter were removed by dry sieving. Pre-cleaned and combusted (550°C) Coors crucibles were weighed to the nearest 0.02 g. Approximately 20 g portions of each dry sediment sample were put in the crucibles and weighed. Samples were combusted at 550°C for five hours, allowed to cool and reweighed to calculate weight loss on ignition.

2. Sulfide

The bottom grab sample from each station was sub-sampled for sulfide analysis. The methods used in the sulfide analysis have been described by Munson (1977). Two replicate sub-samples, weighing approximately 3 g each, were placed in 21 x 50 mm shell vials. The sulfides in each sub-sample were fixed by adding 6 ml of 2N zinc acetate. After sealing the shell vials with plastic

caps, the sediment was mixed with the fixing solution and stored in a refrigerator until laboratory analysis. Analysis was carried out on the sediment plus precipitated zinc sulfide of one sub-sample, the other being saved in case of loss. For analysis, excess zinc acetate solution was removed by suction and the remaining sediment was thoroughly mixed in the vial. From each sub-sample, four replicates of sediment with wet weights between 0.5 and 1.0 g were obtained and placed in individual 50 ml Erlenmeyer flasks containing 5 ml of distilled water. The flasks were stoppered with a vaccine cap, K-882310, fitted with a polypropylene center-well, K-882320 (obtained from Kontes Glass Co., Vineland, New Jersey). The center-wells each contained an accordion-pleated wick (3.8 x 15.25 cm, of Fisher No. 2 filter paper). After stoppering the flasks, two syringe needles, one an inlet and one an exhaust port, provided access to the flask and allowed the air to be flushed out with oxygen-free nitrogen. Flushing was maintained for at least 15 min, after which time the port needles were removed. By means of syringe and needle, at least 1 ml of 2N zinc acetate was added to the center well in order to fix the sulfide released by the subsequent addition of 1 ml of concentrated sulfuric acid to the sediment. After injection of the acid, a liberal coating of rubber cement was brushed over the vaccine cap and allowed to dry, sealing the flask. The flasks were then agitated by gently swirling for 15 sec and allowed to sit

at room temperature for 18 h, a standard trapping time established by Munson (1977).

At the end of the trapping period, each flask was opened, and the wick containing precipitated zinc sulfide removed with forceps and placed in a 250 ml beaker containing approximately 150 ml of distilled water to which had been added exactly 6.00 ml of a 0.025N iodine solution made up as outlined in the Standard Methods for the Examination of Water and Wastewater (American Public Health Association, 1971). Approximately 2.5 ml of concentrated sulfuric acid were immediately pipetted down the side of the beaker while the contents were magnetically stirred. After 30 sec, the solution was rapidly titrated with a standardized 0.025N sodium thiosulfate solution from a 10 ml burette graduated in increments of 0.05 ml. The titration volume was estimated to 0.01 ml. A mean sulfide value for the four replicates was determined, and this mean value was then corrected using an efficiency regression line.

The efficiency (percent recovery) of the method at the 18 h trapping time was determined by analyzing the wicks from 6 standard sulfide samples, covering a range of sulfide concentrations from 0 to 281.4 $\mu\text{g/ml}$. The samples were made up by adding sodium sulfide to distilled water which had been boiled and then cooled in an oxygen-free nitrogen atmosphere. Direct titration of 1 ml aliquots of the standards was used to determine the initial concentration of sulfide.

3. Oxygen consumption rate

The sediment contained in each bottom grab sample was subsampled for measurements of the oxygen consumption rate of the surface sediment. These measurements were carried out onboard ship during each cruise. The water used for the measurements of oxygen consumption rates was collected approximately one meter above the bottom (referred to as "bottom water" in the remainder of this paper) with 1.7 liter Niskin bottles. The concentration of dissolved oxygen in the water before and after incubations was determined by a modification of the Winkler titration, as described by Carpenter (1965). The following is a description of the methods used.

Two replicate sediment cores were removed from the bottom grab sample using clear-plastic butyrate tubes 3.5 x 26.15 cm, with a wall thickness of 1.6 mm. The thickness of the sediment cores obtained ranged from 2 to 11 cm. Each core was immediately filled with bottom water. Two 50 ml Erlenmeyer flasks were filled with the bottom water to determine the initial oxygen concentration by the modified Winkler titration. In order to determine the relative importance of chemical oxidation in producing the observed oxygen consumption rates, an amount of 36% formaldehyde sufficient to result in a final 2% formalin solution was added to the water in one of the replicate core tubes at each station. The oxygen consumption rate of the sediment core to which the formaldehyde

had been added was assumed to be due only to the chemical oxidation of reducing substances in the sediment, whereas consumption in the unpoisoned core tube was assumed to be due to biological plus chemical oxygen demand. Each core was then sealed and placed in its own continuous-flow water bath (Fig. 3) to maintain ambient water temperatures. The water baths consisted of clear plastic tubes, 6.8 x 21 cm, connected by rubber hoses to the ship's sub-surface hull pump. The temperature of the water baths equalled that of the sub-surface waters of the Lower Bay, and never differed from the bottom waters of the Lower Bay by more than 2°C. The water above the sediment in the core tubes was magnetically stirred at a rate sufficient for mixing but with minimal disturbance of the sediment surface. The sediment cores were incubated for 3 hours. At the end of the incubation period the water above the sediment was siphoned into two 50 ml Erlenmeyer flasks. The dissolved oxygen concentration of the water was then determined by the modified Winkler titration. The difference between the initially measured dissolved oxygen concentration of the bottom water and the dissolved oxygen of the water above the sediment at the end of the incubation period was used in calculating the biological and chemical oxygen consumption rates of the surficial sediments in terms of $\text{mg } Q_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$.

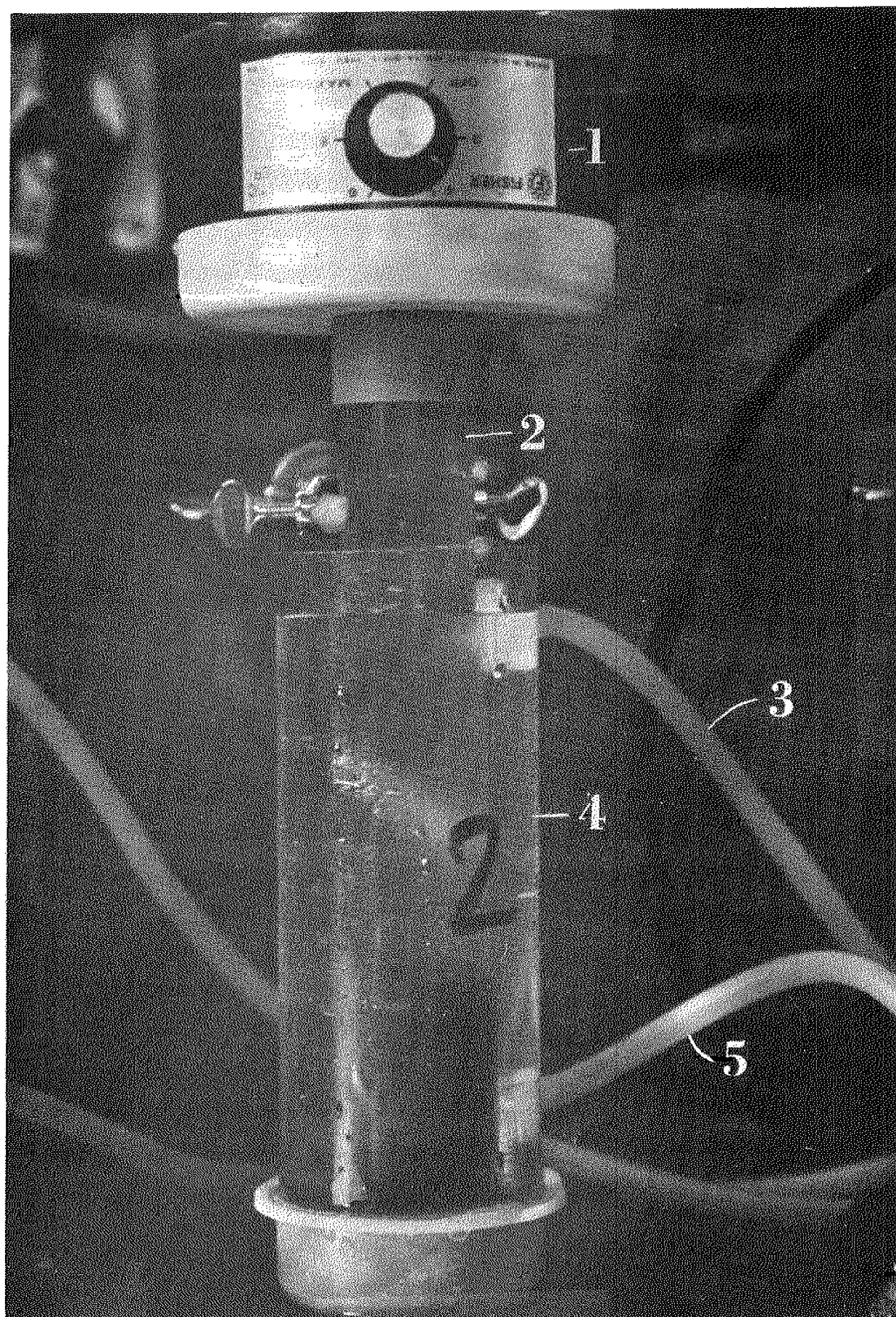
4. Temperature and dissolved oxygen profiles

The temperature and dissolved oxygen concentration of the bottom water were measured at each station on all five cruises.

Figure 3

Photograph of a sediment core in a continuous-flow water bath during an oxygen consumption experiment.

- 1 --- Magnetic stirrer
- 2 --- Core tube
- 3 --- Overflow
- 4 --- Water bath in plastic core liner
- 5 --- Inflow from ship's hull pump



In addition, the temperature and dissolved oxygen concentration of the water at various depths in the water column were also measured on the May and June cruises. Water samples for the temperature and dissolved oxygen determinations were collected with 1.7 liter Niskin bottles. The temperature of the collected samples was measured onboard ship with mercury thermometers. The dissolved oxygen concentration was determined by the modified Winkler titration. On August cruise, temperature profiles in the water column were obtained with an Inter-Ocean model 550 CTD recorder.

5. Salinity

All Niskin water samples collected on the June cruise were analyzed for salinity with a Hytech model 6220 salinometer to obtain vertical salinity profiles. Salinity profiles on the August cruise were obtained with the CTD. The salinity data were used in conjunction with the temperature and dissolved oxygen data to calculate the oxygen percent saturation of each water sample collected. The Sigma-T of each water sample was calculated so that any vertical density stratification which may have existed at a given station could be identified.

Salinity measurements were not made during the February, March, and May cruises. In order to estimate the present saturation of oxygen in the bottom waters of the Lower Bay during the February, March, and May cruises, salinity data were obtained from

data collected in 1973 and 1974 by Parker et al. (1976). Tidal, spatial, and seasonal changes in salinity in the Sandy Hook-Rockaway Point transect (see Fig. 2) during five cruises between November, 1973 and June, 1974 were used to estimate the oxygen percent saturation of the bottom waters of the Lower Bay during the February, March, and May cruises of this investigation. The validity of this extrapolation was investigated by comparing the salinity data collected by Parker et al. during their June, 1974 cruise to the salinity data collected during the June, 1978 cruise of the current investigation.

Results

Data obtained from the various analyses of sediments and bottom water at each station sampled during the study period are listed in Appendix A. The stations are arranged in the Appendix according to two criteria: 1) the station's location relative to Ambrose Channel--either on the East Bank or the West Bank; and 2) the nature of the seabed at a given station--either dredged or undisturbed by dredging activity.

Sulfide and organic content of sediments

Figure 4 shows the relationship between the organic carbon (percent loss on ignition) and the sulfide present in the surface sediments during the March, May, June, and August cruises. Sulfide was not measured during the February cruise. There was a strong correlation between the organic carbon and sulfide present in the surface sediments during all four cruises ($r = 0.99, 0.95, 0.87,$ and 0.93 , respectively). One would expect this, since the sulfide present in the sediments is the by-product of the decomposition of organic carbon by sulfate-reducing bacteria within the sediments.

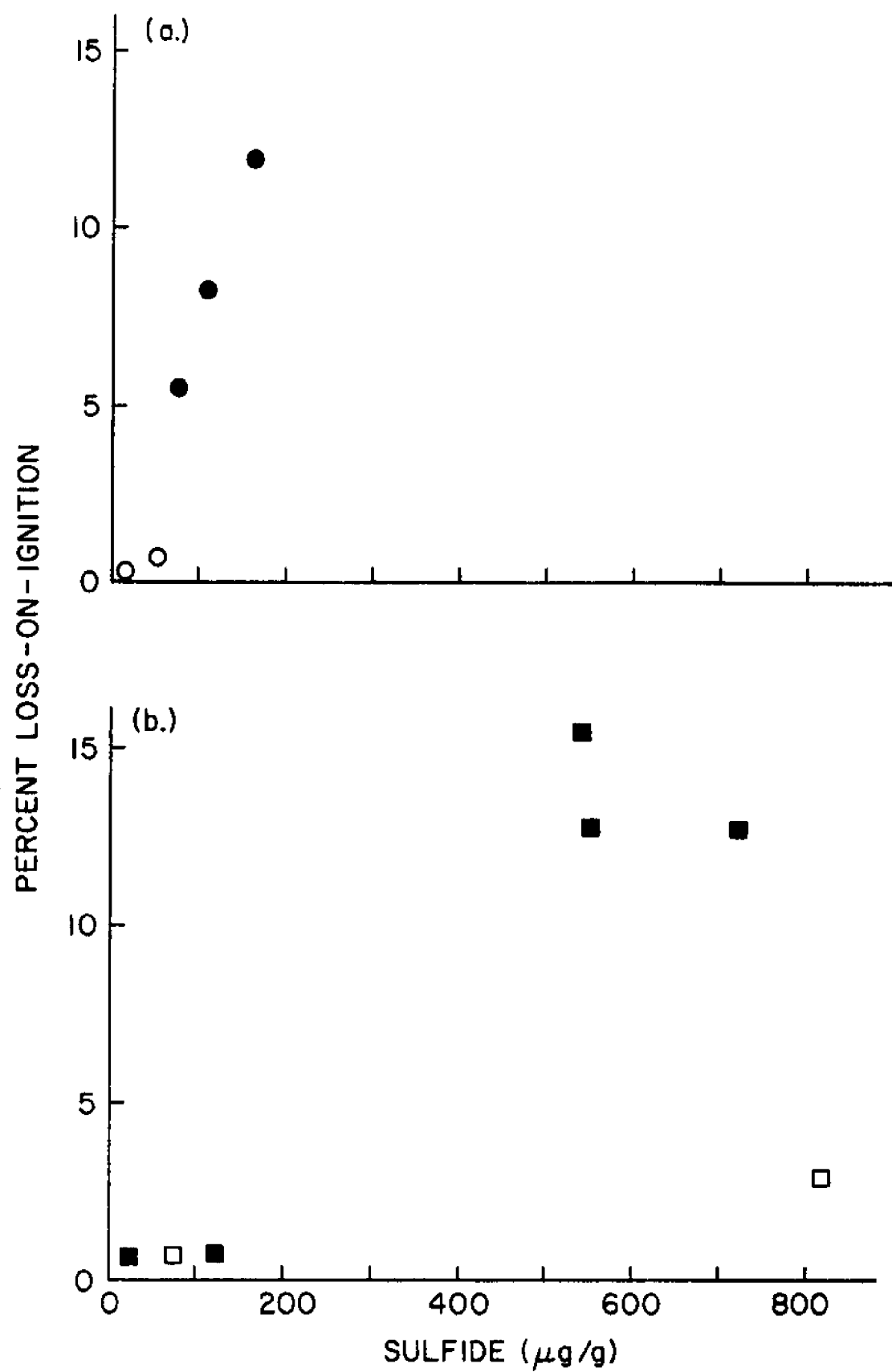
Figure 5 is a graph of the efficiency regression line used for calculating the sulfide content of the sediments. Using the mean of four replicates, the maximum sensitivity of the method is $\pm 5.48 \mu\text{g}$ (Munson, 1977).

Figure 4

The relationship between the organic carbon (percent loss on ignition) and sulfide present in the surficial sediments.

Symbol Key

<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
(a) 21-III-78.....	○	●
(b) 17-V-78.....	□	■
(c) 27-VI-78.....	△	▲
(d) 8-VIII-78.....	◇	◆



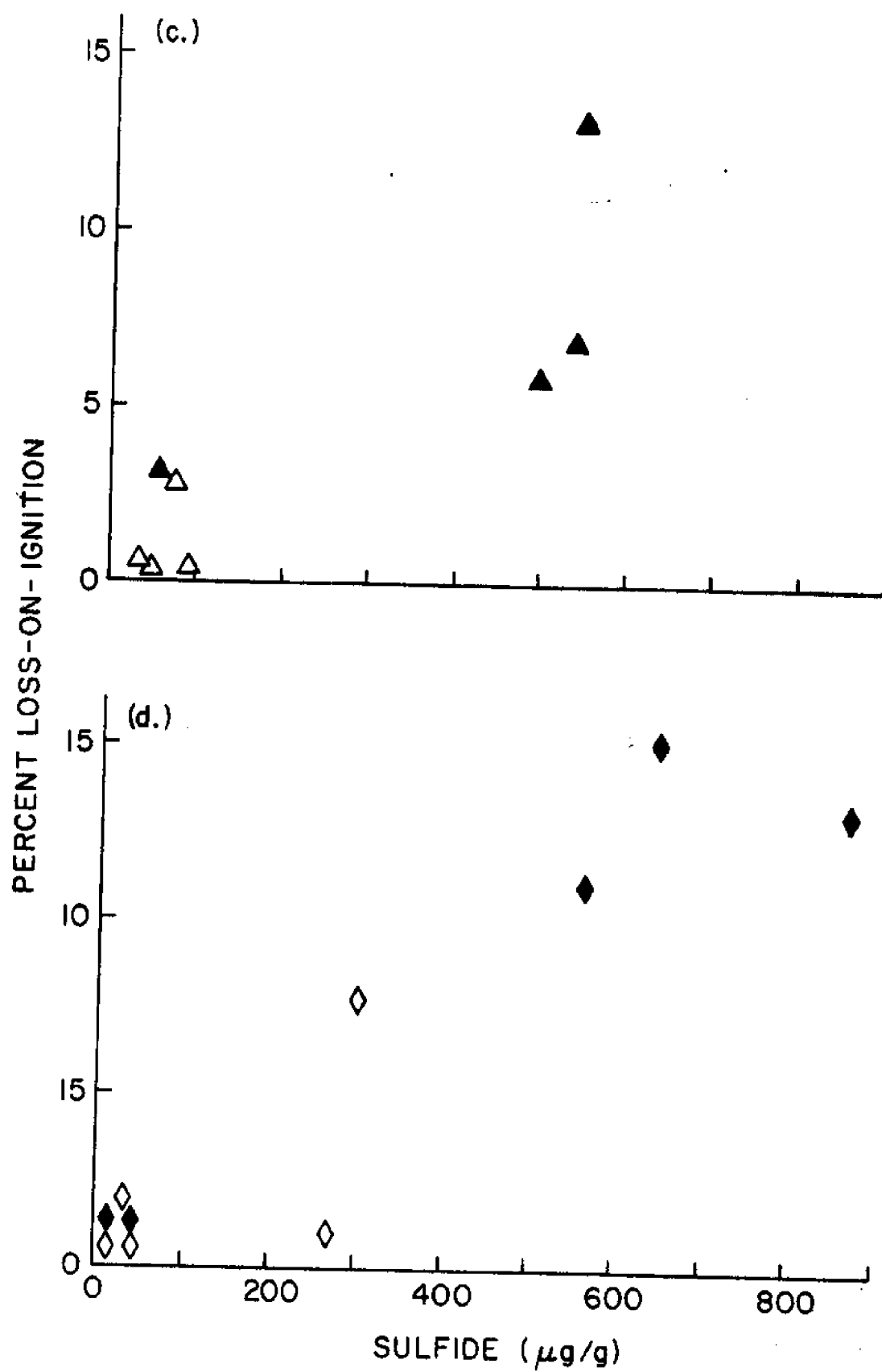
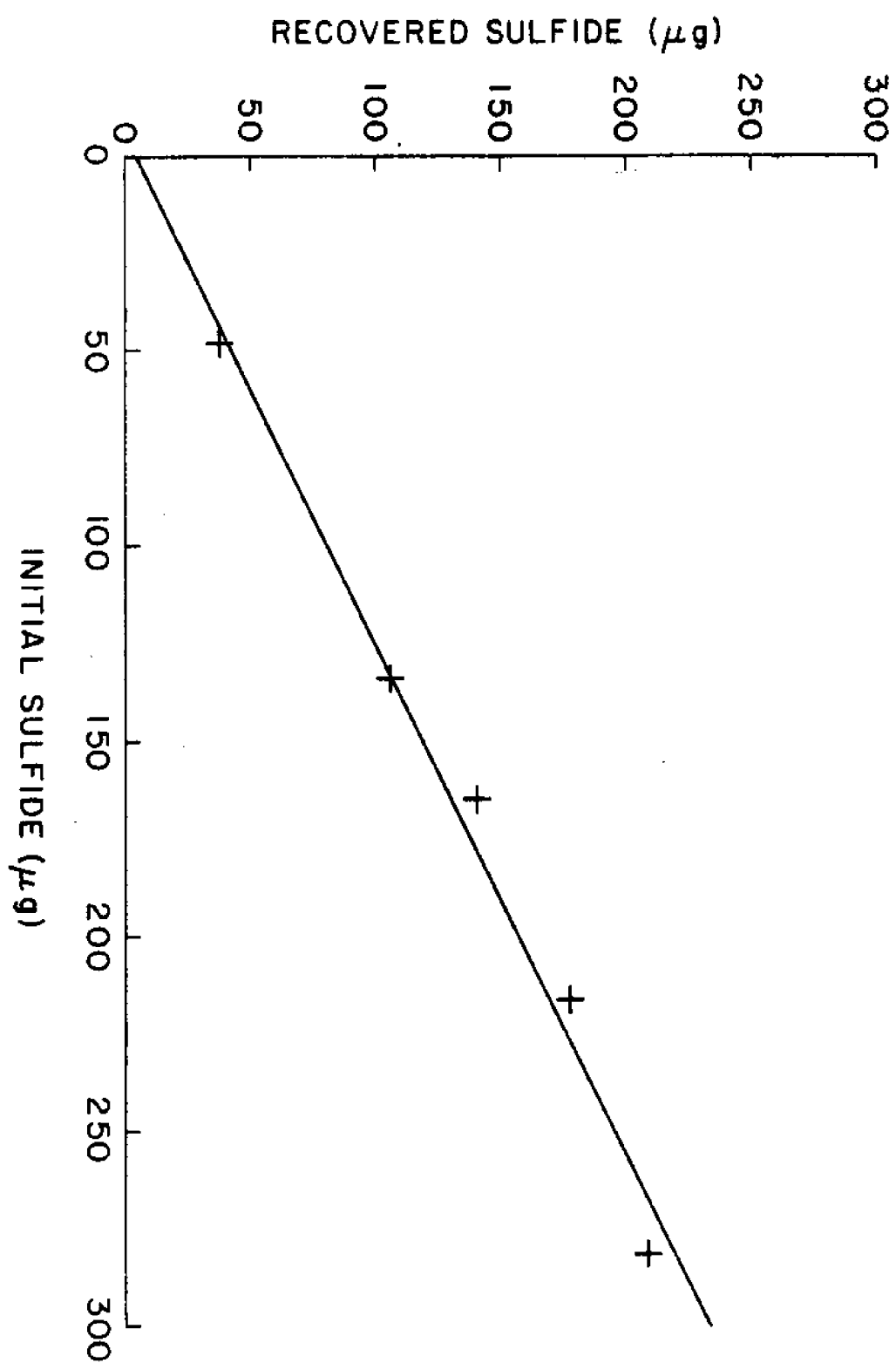


Figure 5

Initial amount of sulfide in six standard solutions (abscissa) and amount of sulfide recovered in wicks (ordinate). Equation for regression line is $Y = 3.4674 + 0.7720X$.



The surface sediments in dredged areas on the West Bank have higher percentages of organic carbon and larger quantities of sulfide than those on the East Bank (see also Appendix A). The surface sediments in undisturbed areas on the West Bank resemble those of dredged and undisturbed areas on the East Bank in terms of organic carbon and sulfide. The largest quantities of organic carbon and sulfide were measured in the surface sediments of the deepest (20 m) dredged hole (see Fig. 2-Area "C") on the West Bank.

Oxygen concentration of the bottom water

Figure 6 illustrates an approximate 54 percent decrease in the oxygen concentration of the bottom water as the temperature of the bottom water increased from February (2°C) to August (22°C). Stations sampled in February and March had the lowest temperature and the highest oxygen concentrations. Stations sampled in May and June had much higher temperatures and considerably lower oxygen concentrations. By August, the water temperature had reached a maximum and the oxygen concentration a minimum.

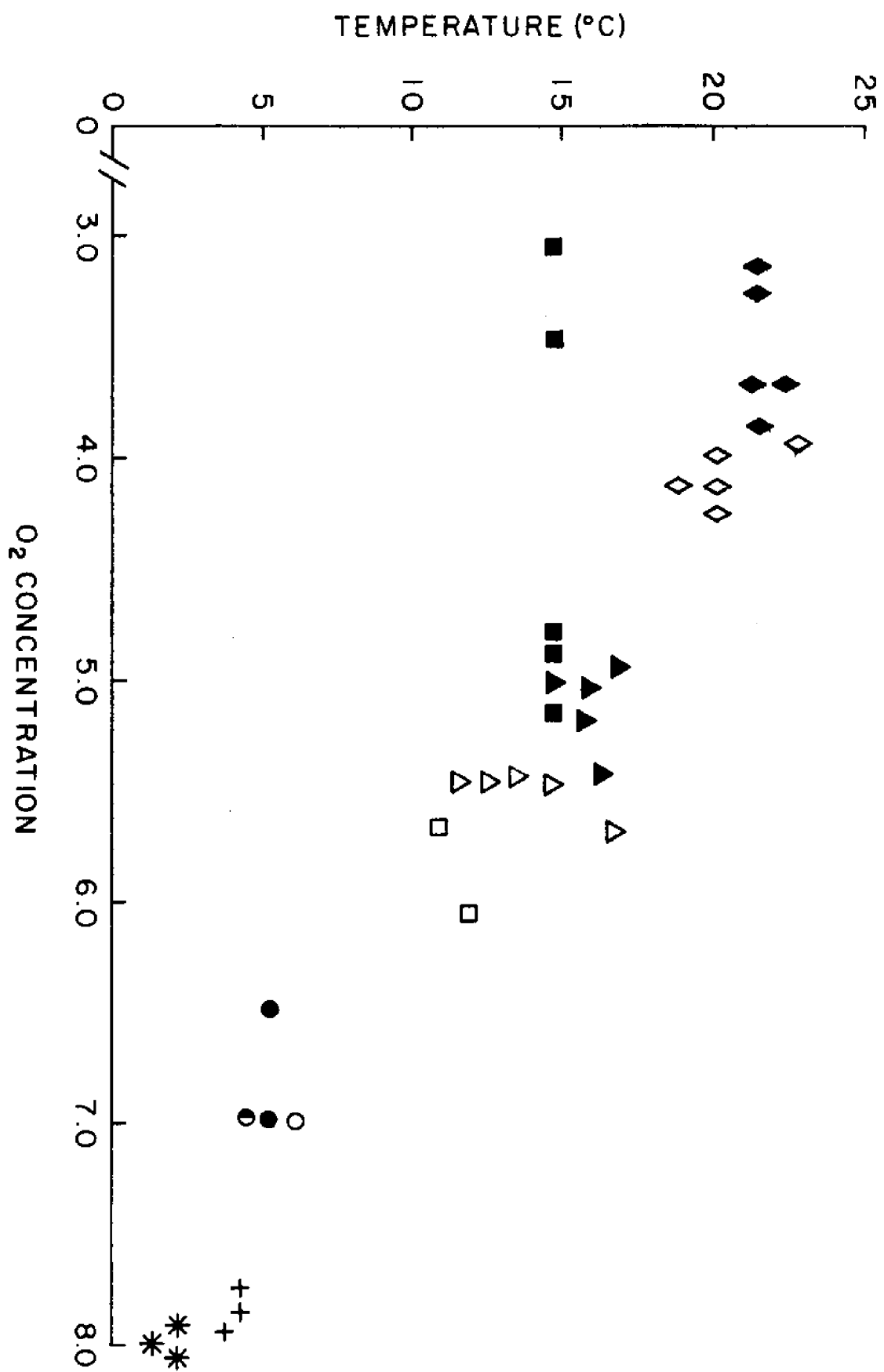
Figure 6 also illustrates that, with the exception of the March cruise, stations sampled during a given cruise tend to fall into two groups, based on their location relative to Ambrose Channel. In February, all of the stations had about the same oxygen concentration, but stations on the East Bank had higher bottom water temperatures. In May, June, and August, stations on

Figure 6

The relationship between the temperature and dissolved oxygen concentration of the bottom water.

Symbol Key

<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
2-II-78.....	+	*
21-III-78.....	○	●
17-V-78.....	□	■
27-VI-78.....	△	▲
8-VIII-78.....	◇	◆



the East Bank tended to have lower bottom water temperatures and higher oxygen concentrations than stations on the West Bank.

It should also be noted from the graph that four stations, two sampled in May (43 and 44) and two in August (58 and 59), had much lower bottom water oxygen concentrations than any of the other stations sampled during their respective cruises (i.e. at similar temperatures). All four of these stations are located on the West Bank in a hole (see Fig. 2-Area "C") which had been dredged to 27 m in 1971 and since back-filled to its current depth of 18 m. The oxygen and temperature data are summarized in Appendix A.

Oxygen percent saturation of the bottom water

The salinity data collected by Parker et al. (1976) in the Sandy Hook-Rockaway Point transect between November, 1973 and June, 1974 were used to estimate the oxygen percent saturation of the bottom waters of the Lower Bay during the February, March, and May cruises of the current investigation. Since the salinity of the waters of the Lower Bay at any given time is dependent on the stage of the tide, only samples collected at similar tide stages and locations were compared. For example, the salinity of the bottom water on the East Bank of Ambrose Channel in June, as measured by Parker et al., was 29.9 parts per thousand (ppt) at flood tide. The salinity of the bottom water on the East Bank in June, as measured during the current investigation (average of five

stations), was 30.2 ppt at flood tide. Using the average temperature of the bottom water at the East Bank stations (15°C), as measured during the June cruise of the current investigation, the oxygen solubility of water with a salinity of 30.2 ppt is $5.7 \text{ mL } \text{O}_2 \cdot \text{l}^{-1}$ (Weiss, 1970). Using the temperature of the bottom water on the East Bank (16.4°C), as measured by Parker et al. the oxygen solubility of water with a salinity of 29.9 ppt is $5.8 \text{ mL } \text{O}_2 \cdot \text{l}^{-1}$. Thus, the oxygen percent saturation values of the bottom water estimated from the salinity data of Parker et al. are in good agreement with those calculated from the salinity data collected during the current investigation.

Figure 7 illustrates that there was an approximate 33 percent decrease in the oxygen percent saturation of the bottom water as the temperature of the bottom water increased from February to August. Stations sampled in February and March had the lowest temperatures and the highest oxygen percent saturation values. Stations sampled in May and June had much higher temperatures but only slightly lower oxygen percent saturation values. By August, the water temperature had reached a maximum and the oxygen percent saturation a minimum.

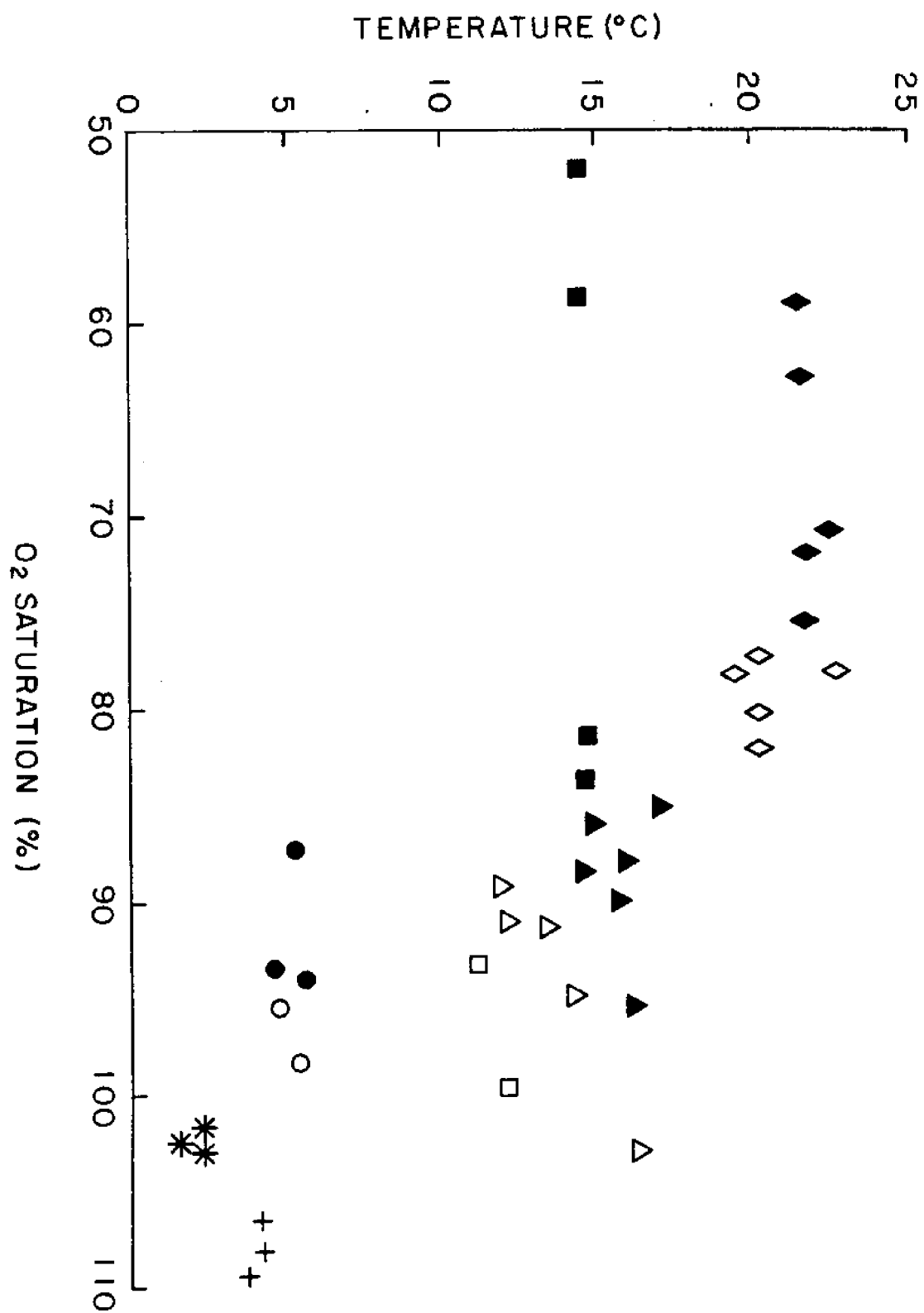
Figure 7 also illustrates that with respect to temperature and oxygen percent saturation, stations on the East Bank tended to differ from those on the West Bank during all of the sampling times except March. In February, May, June, and August the West Bank stations had slightly lower oxygen percent saturation values than

Figure 7

The relationship between temperature and the oxygen percent saturation of the bottom water.

Symbol Key

<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
2-II-78.....	+	*
21-III-78.....	○	●
17-V-78.....	□	■
27-VI-78.....	△	▲
8-VIII-78.....	◇	◆



the East Bank stations. Stations 43, 44, 58, and 59 (Fig. 2-Area "C") are once again exceptions, with oxygen percent saturation values significantly lower than any of the other stations sampled during their respective cruises.

Figure 8 is a plot of percent loss on ignition of the sediment versus oxygen percent saturation of the bottom water at all stations sampled during the five cruises. The data plots for the March, May, and August cruises illustrate a negative correlation ($r = -0.88$, -0.78 , and -0.81 , respectively) between the oxygen percent saturation of the bottom water and the organic carbon content of the sediments. As the organic carbon content of the sediments increased, the oxygen percent saturation of the bottom water decreased. In general, the sediments of the West Bank stations had a higher organic carbon content and the bottom waters had lower oxygen percent saturation values than the East Bank stations. The data from the February and June cruises illustrate the same trends, though the correlation is not as high ($r = -0.61$ and -0.52 , respectively).

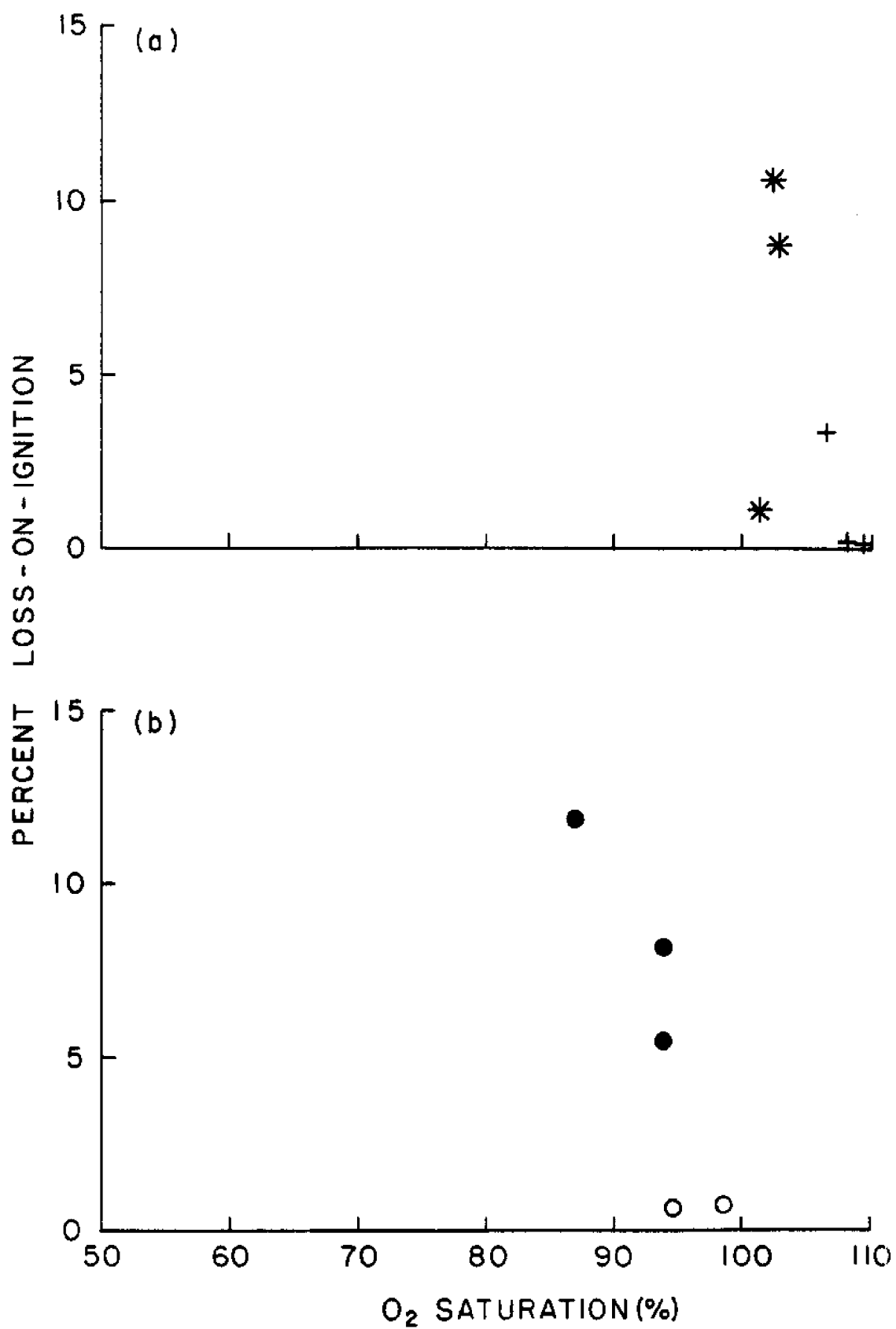
Figure 9 is a plot of the sulfide content of the sediments versus the oxygen percent saturation of the bottom water at all stations sampled during the March and August cruises. Figure 9 illustrates a negative correlation ($r = -0.91$ and -0.79 , respectively) between the sulfide content of the sediments and the oxygen percent saturation of the bottom water during the March

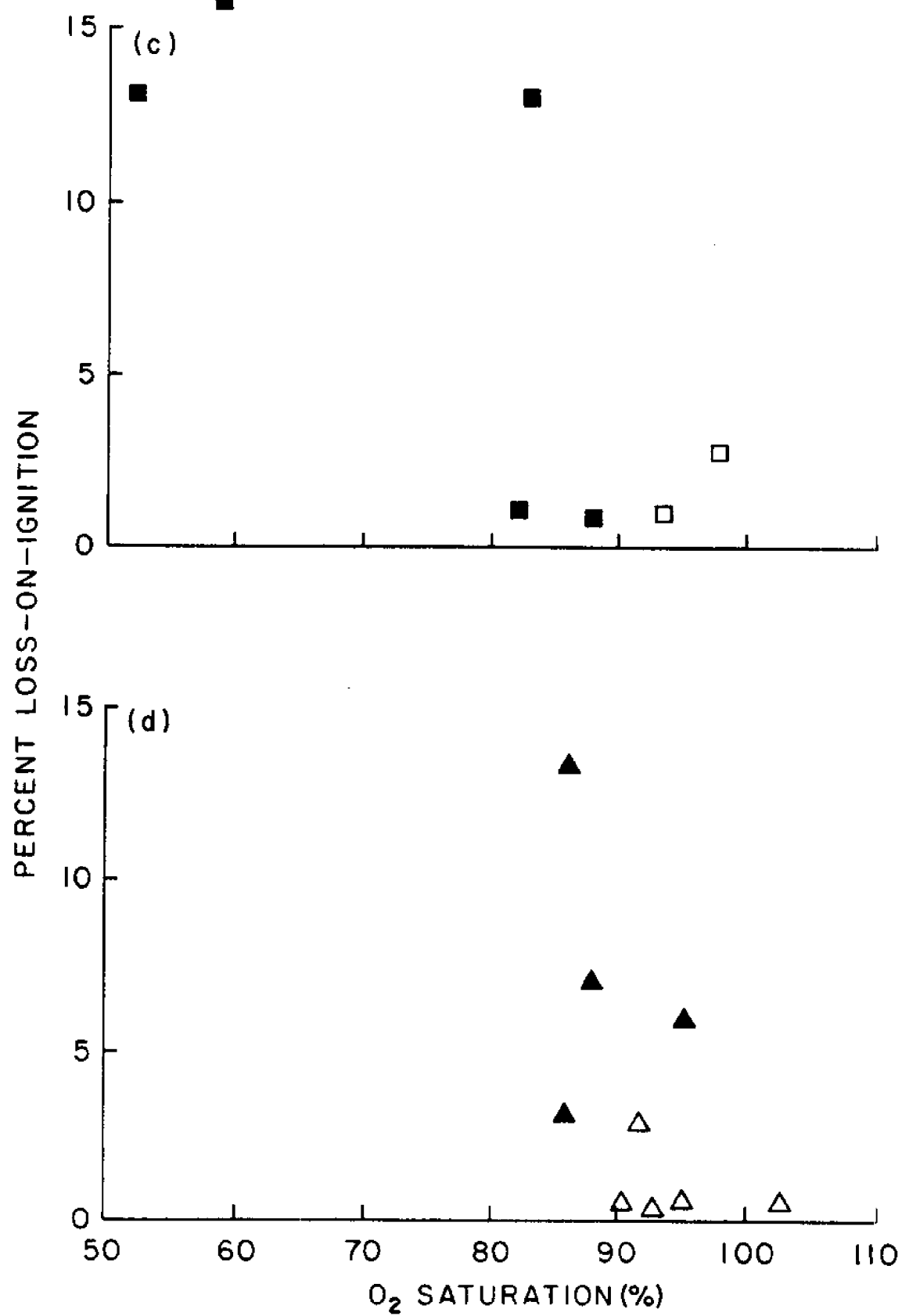
Figure 8

The relationship between the organic carbon (percent loss on ignition) of the surficial sediments and the oxygen percent saturation of the bottom water.

Symbol Key

<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
(a) 2-II-78.....	+	*
(b) 21-III-78.....	○	●
(c) 17-V-78.....	□	■
(d) 27-VI-78.....	△	▲
(e) 8-VIII-78.....	◇	◆





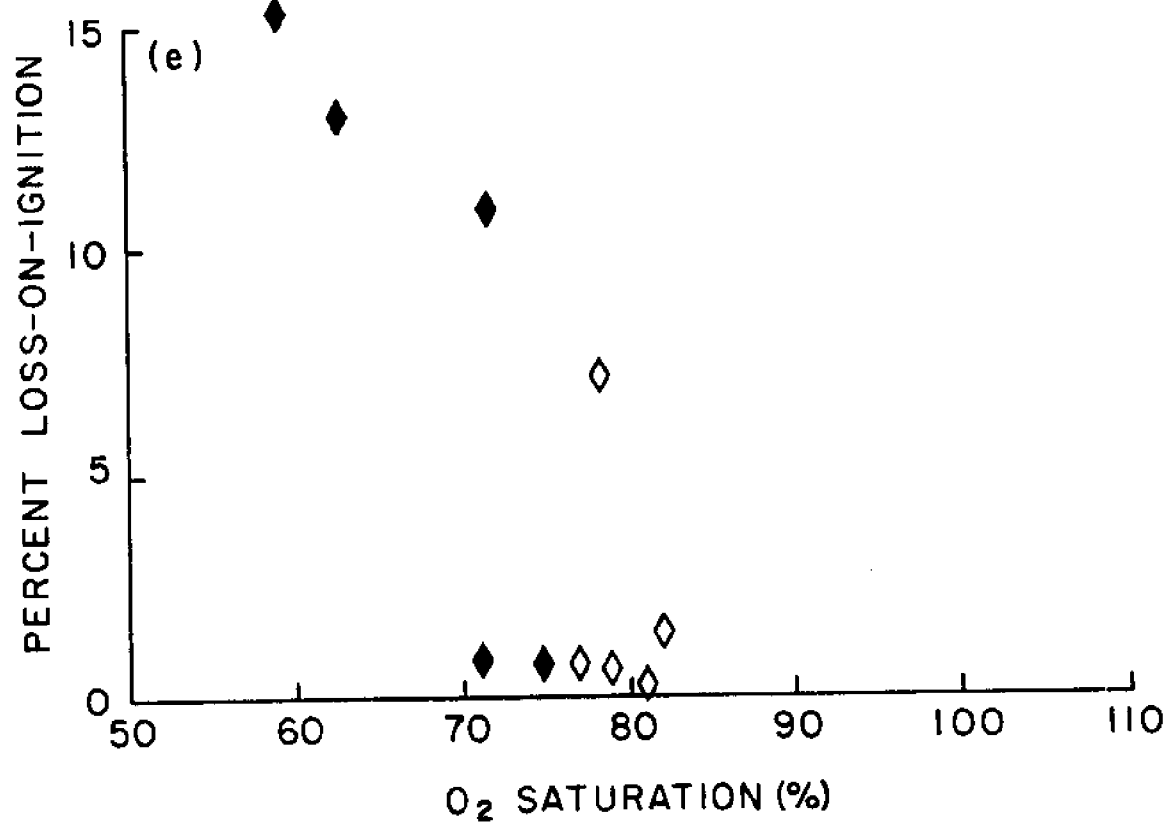
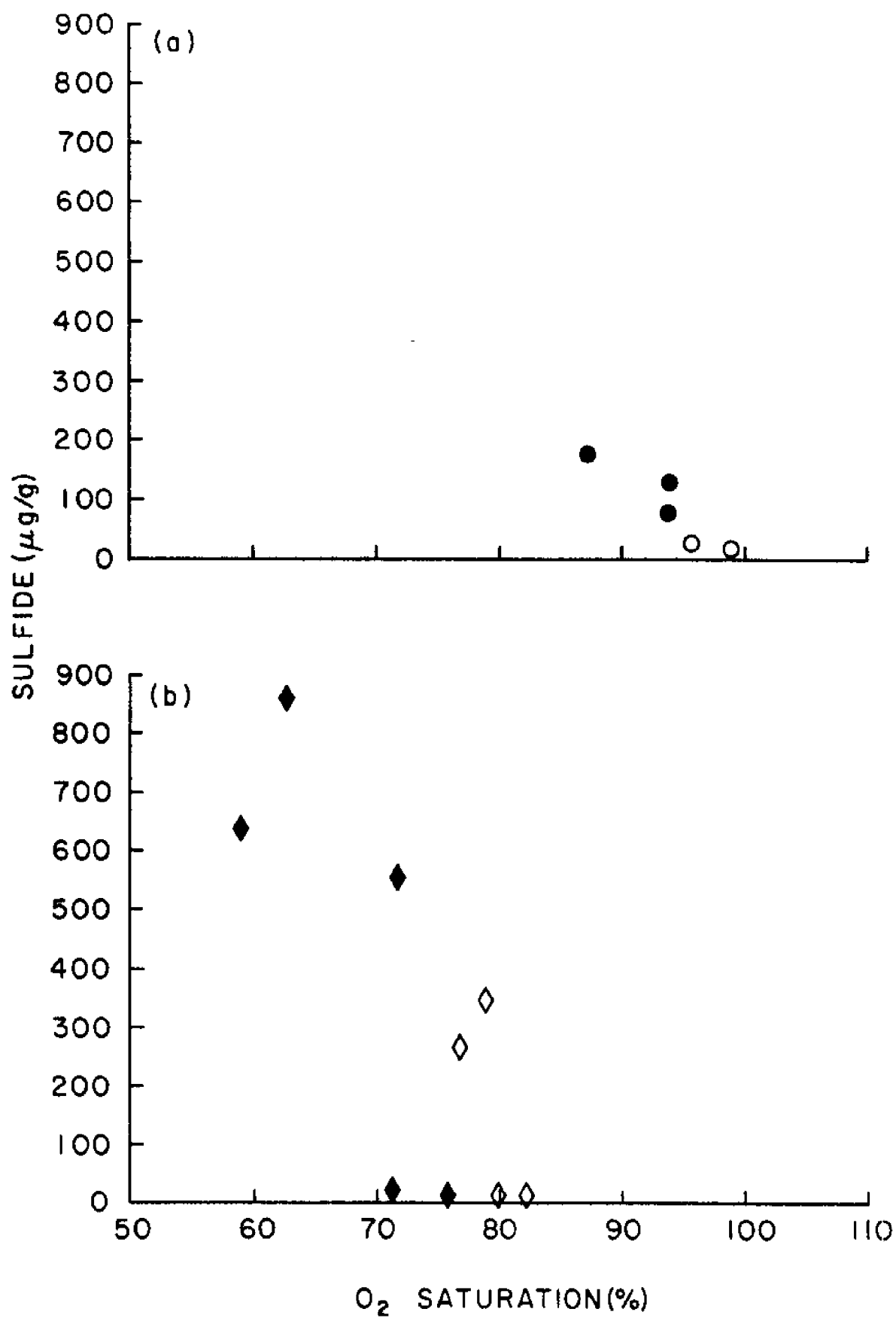


Figure 9

The relationship between the sulfide content of the surficial sediments and the oxygen percent saturation of the bottom water.

Symbol Key		
<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
(a) 21-III-78.....	○	●
(b) 8-VIII-78.....	◇	◆



and August cruises. As the sulfide content of the sediments increased, the oxygen percent saturation of the bottom water decreased.

Oxygen consumption rate of the surficial sediments

Figure 10 illustrates that there was an increase in the total oxygen consumption rate of the surficial sediments as the temperature of the bottom water increased from February to July. However, the correlation between total oxygen demand and temperature is weak ($r = 0.54$). Stations tend to fall into two groups, with those sampled in February and March having approximately 70 percent lower temperatures and about 50 percent lower oxygen consumption rates than stations sampled in May and June. There were no consistent differences between total oxygen demand at East and West Bank stations during any of the cruises in which total oxygen demand was calculated.

Figure 11 illustrates that there was little correlation between the organic carbon content of the sediments and the total oxygen consumption rate of the sediments during the February, May, and June cruises ($r = 0.18$, -0.02 , and -0.49 , respectively).

Figure 12 illustrates a correlation ($r = 0.80$ and 0.96 , respectively) between the sulfide content of the sediments and the chemical oxygen demand of the sediments during the May and August cruises. As the sulfide content of the sediments increased, the

Figure 10

The relationship between the temperature of the bottom water and the total oxygen consumption rate of the surficial sediments.

Symbol Key		
<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
2-II-78.....	+	*
21-III-78.....	○	●
17-V-78.....	□	■
27-VI-78.....	△	▲

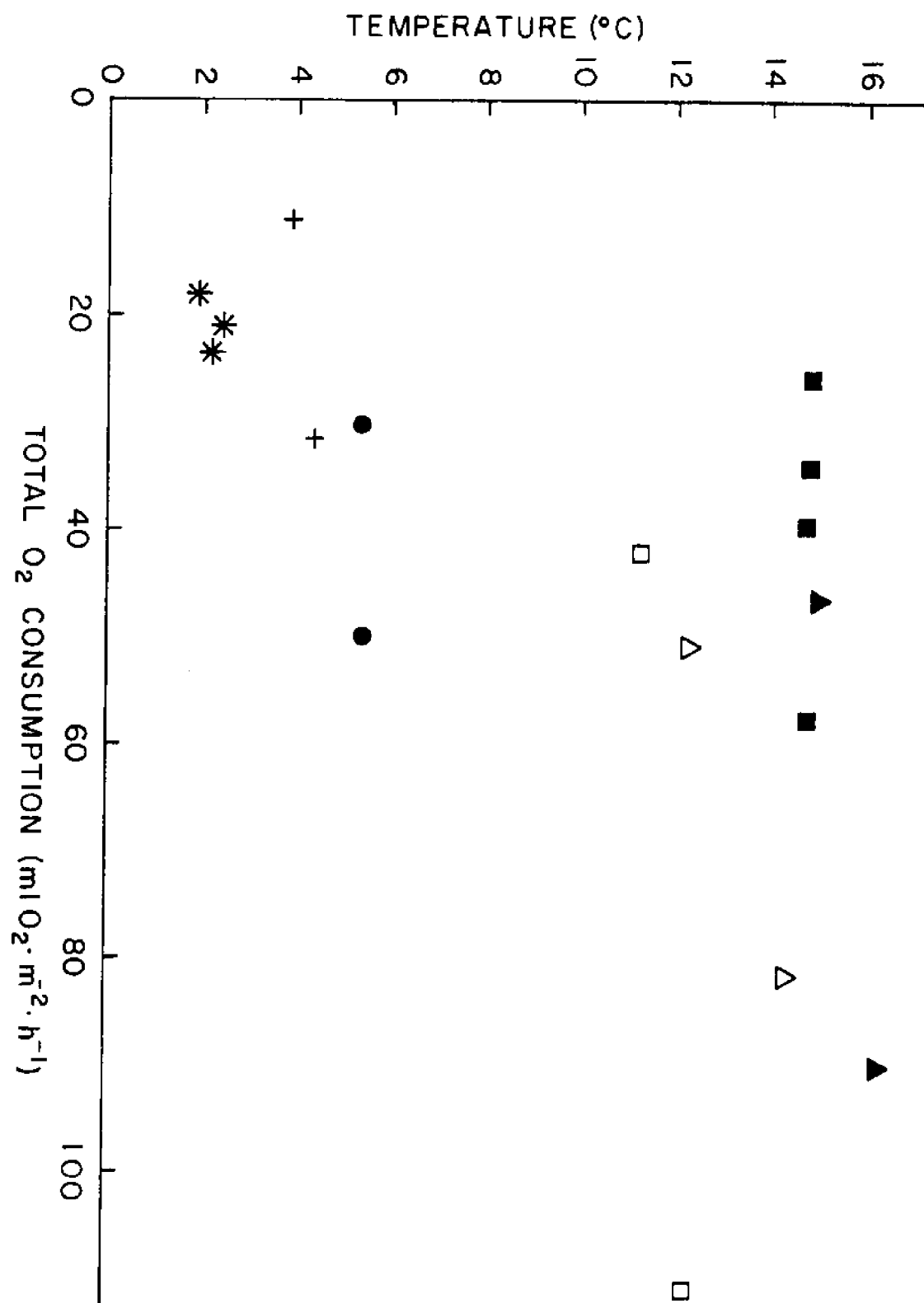
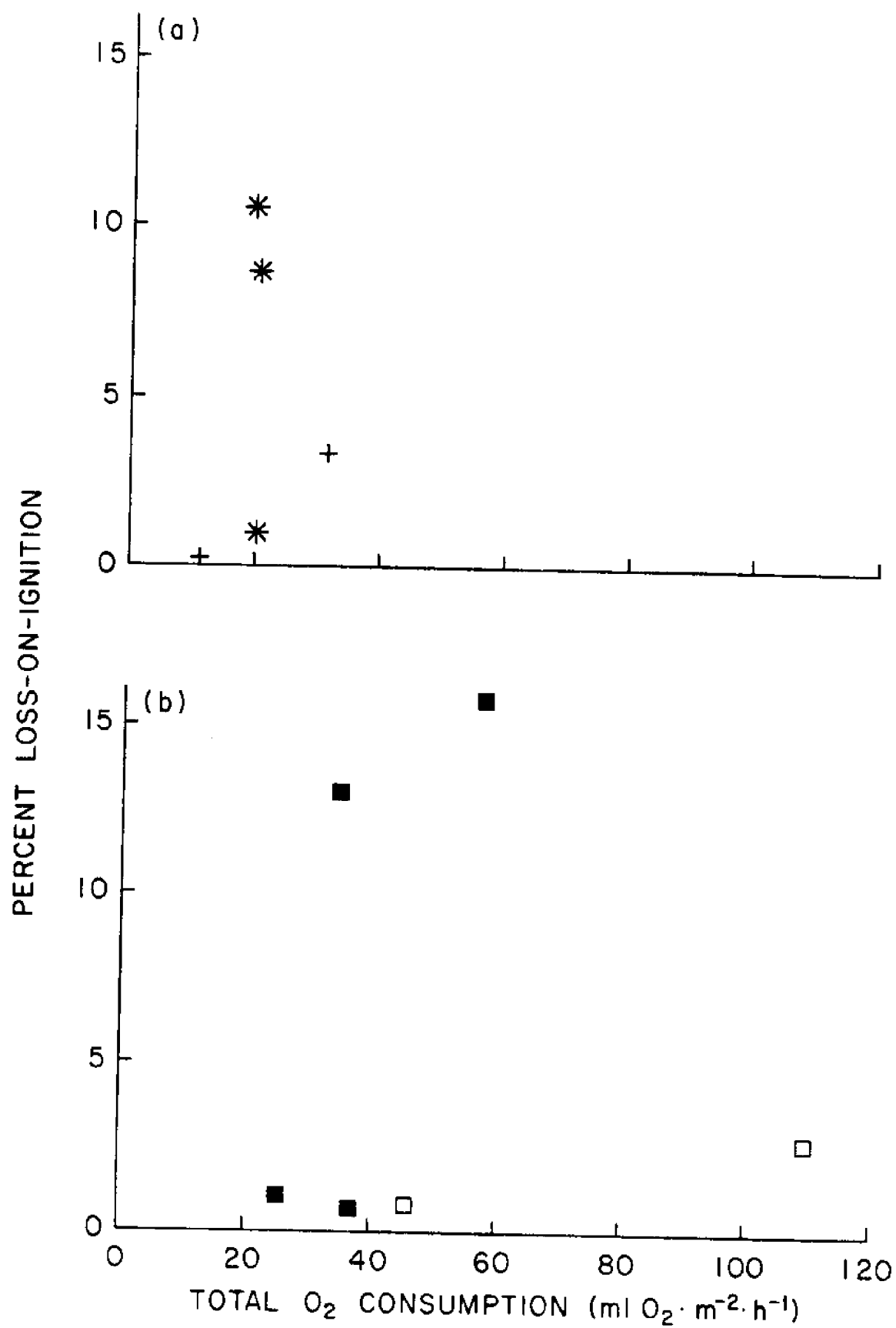


Figure 11

The relationship between the organic carbon (percent loss on ignition) content of the surficial sediments and the total oxygen consumption rate of the surficial sediments.

Symbol Key

<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
(a) 2-II-78.....	+	*
(b) 17-V-78.....	□	■
(c) 27-VI-78.....	△	▲



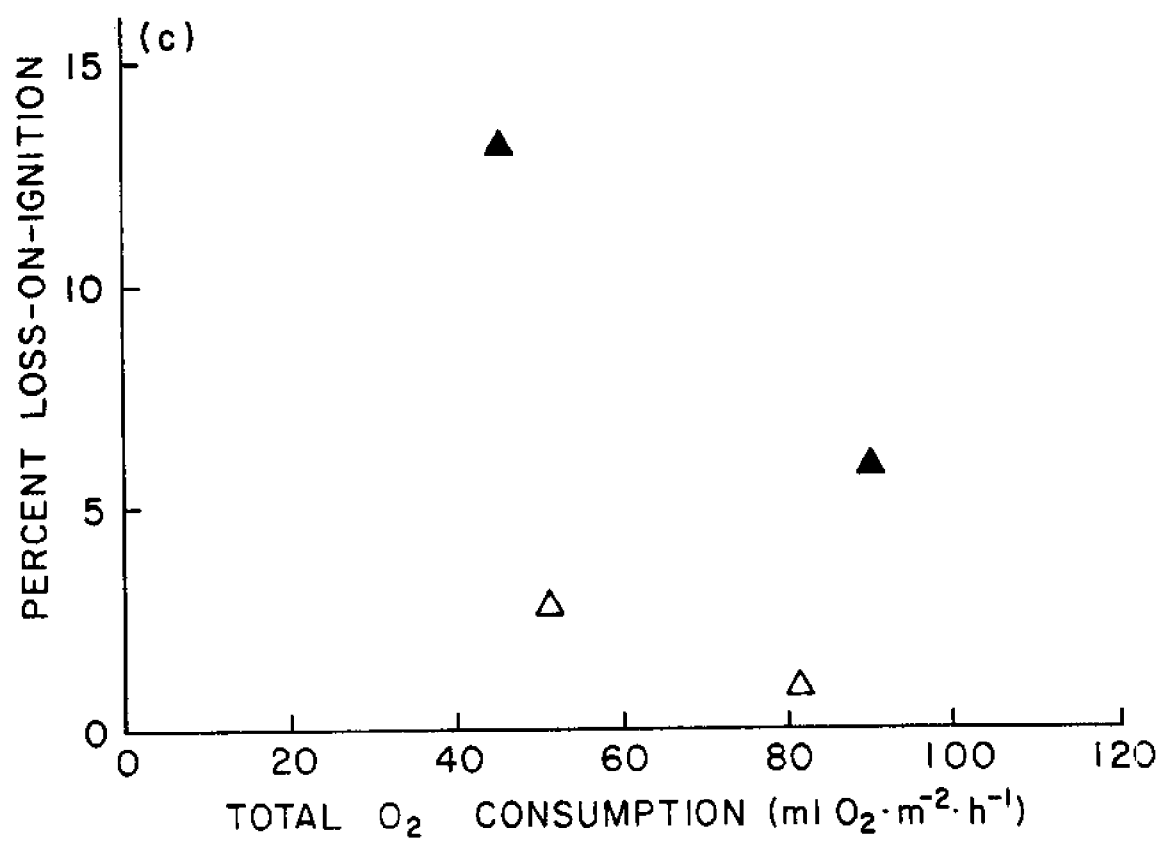
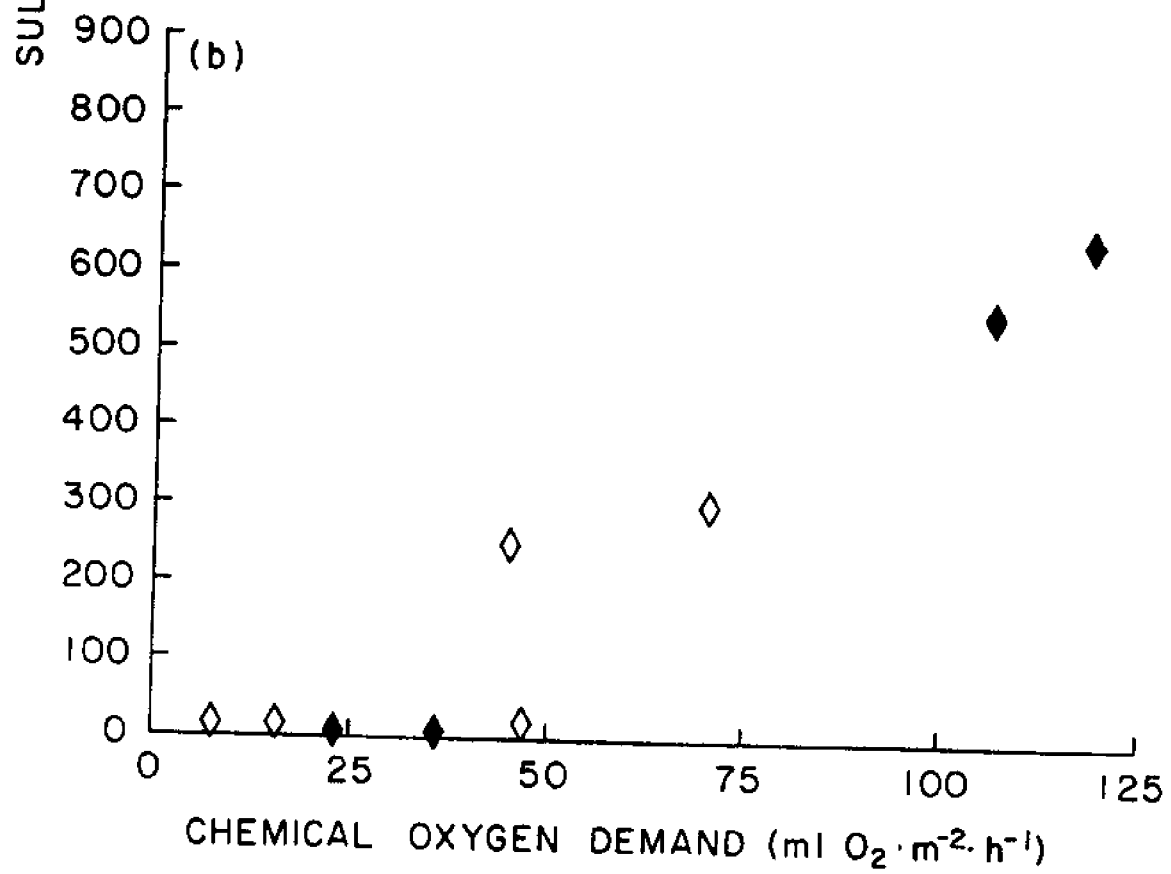
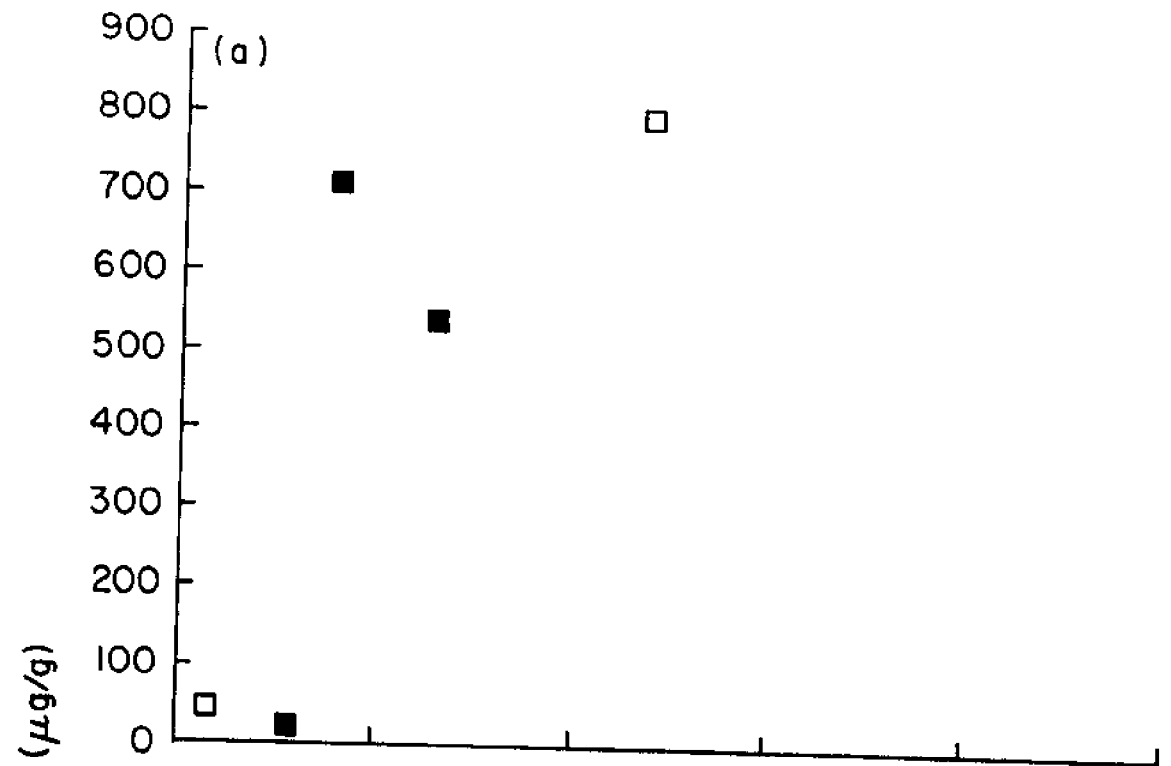


Figure 12

The relationship between the sulfide content of the surficial sediments and the chemical oxygen demand of the surficial sediments.

Symbol Key		
<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
(a) 17-V-78.....	□	■
(b) 8-VIII-78.....	◇	◆



COD of the sediments increased as well. It should also be noted from the figure that the highest sulfide concentrations and COD values measured during August were obtained from samples collected on the bottom of the deeply dredged hole (Fig. 2-Area "C") on the West Bank (stations 58 and 59).

Figure 13 illustrates that there was little correlation ($r = -0.20$) between the total oxygen consumption rate of the surficial sediments and the oxygen percent saturation of the bottom water during any of the cruises in which total oxygen consumption rates were determined. Figure 14, on the other hand, illustrates a negative correlation ($r = -0.79$) between the chemical oxygen demand of the sediments and the oxygen percent saturation of the bottom water during August. As the COD of the sediments increased, the oxygen percent saturation of the bottom water decreased.

Vertical profiles of oxygen concentration and Sigma-T

Data obtained from measurements of the dissolved oxygen concentration, temperature, and salinity at various depths in the water column during the May, June, and August cruises are summarized in Appendix B. Vertical profiles of oxygen concentration versus depth were plotted from the data obtained on the May and June cruises (Figs. 15 and 16). These figures illustrate that there was a gradual decrease in the oxygen concentration with depth at most of the stations. There were three exceptions, however, where the decrease was more rapid. At Station 43, sampled during

Figure 13

The relationship between the total oxygen consumption rate of the surficial sediments and the oxygen percent saturation of the bottom water.

Symbol Key

<u>Cruise date</u>	<u>East Bank stations</u>	<u>West Bank stations</u>
2-II-78.....	+	*
21-III-78.....	○	●
17-V-78.....	□	■
27-VI-78.....	△	▲

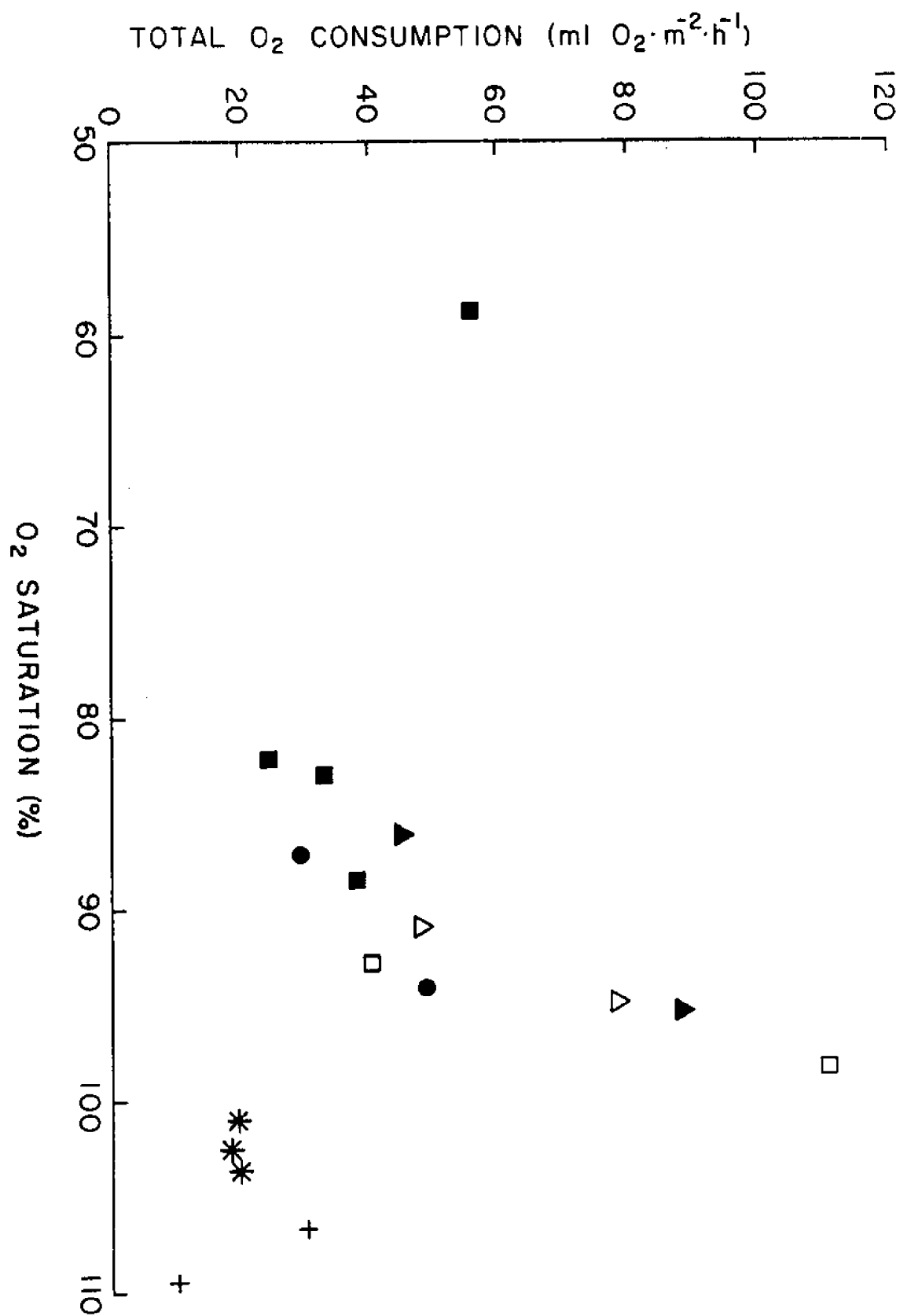


Figure 14

The relationship between the chemical oxygen demand of the surficial sediments and the oxygen percent saturation of the bottom water on 8-VIII-78 at East Bank (◊) and West Bank (◆) stations.

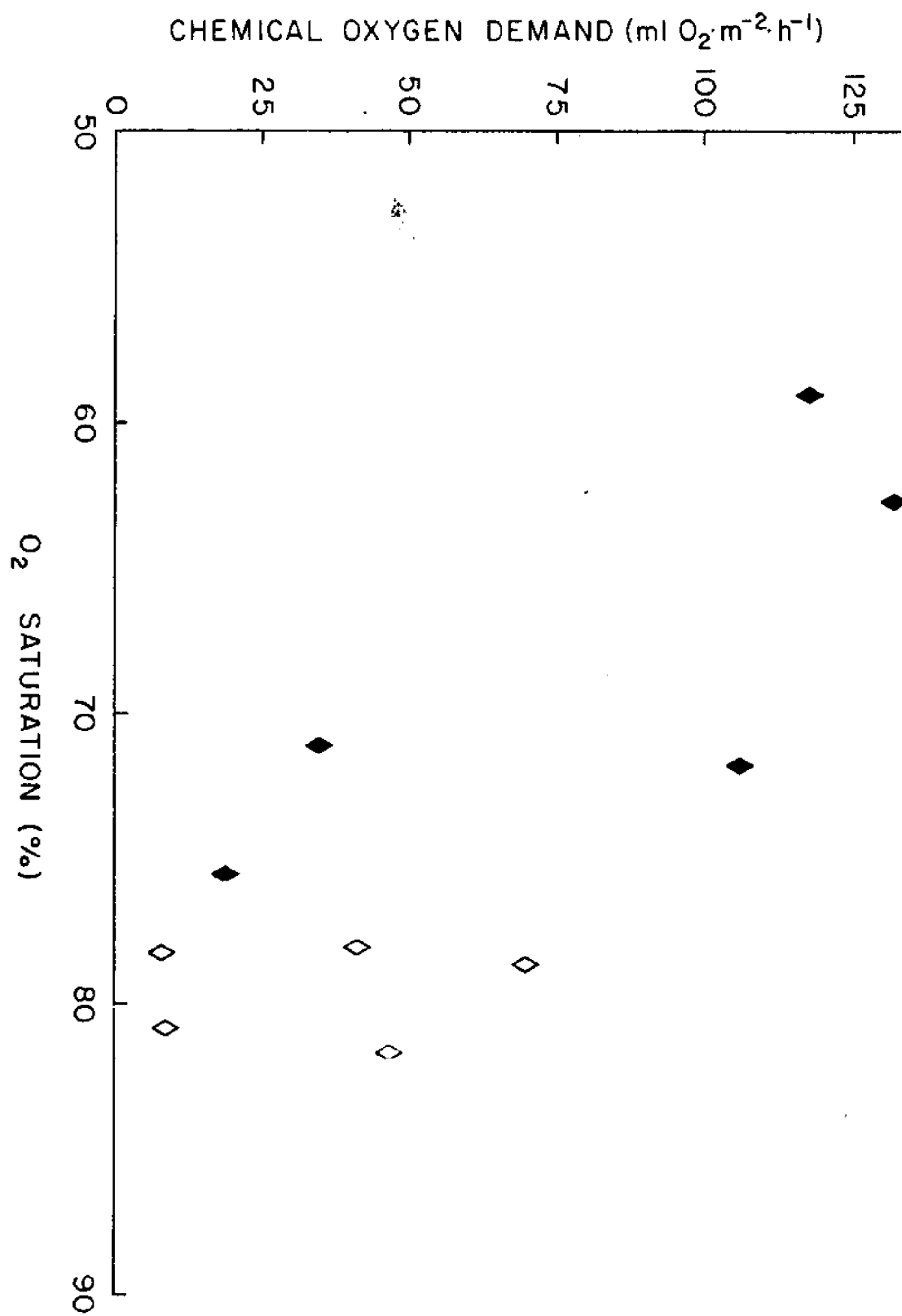


Figure 15

Vertical profile of the dissolved oxygen concentration versus depth at all stations sampled on 17-V-78.

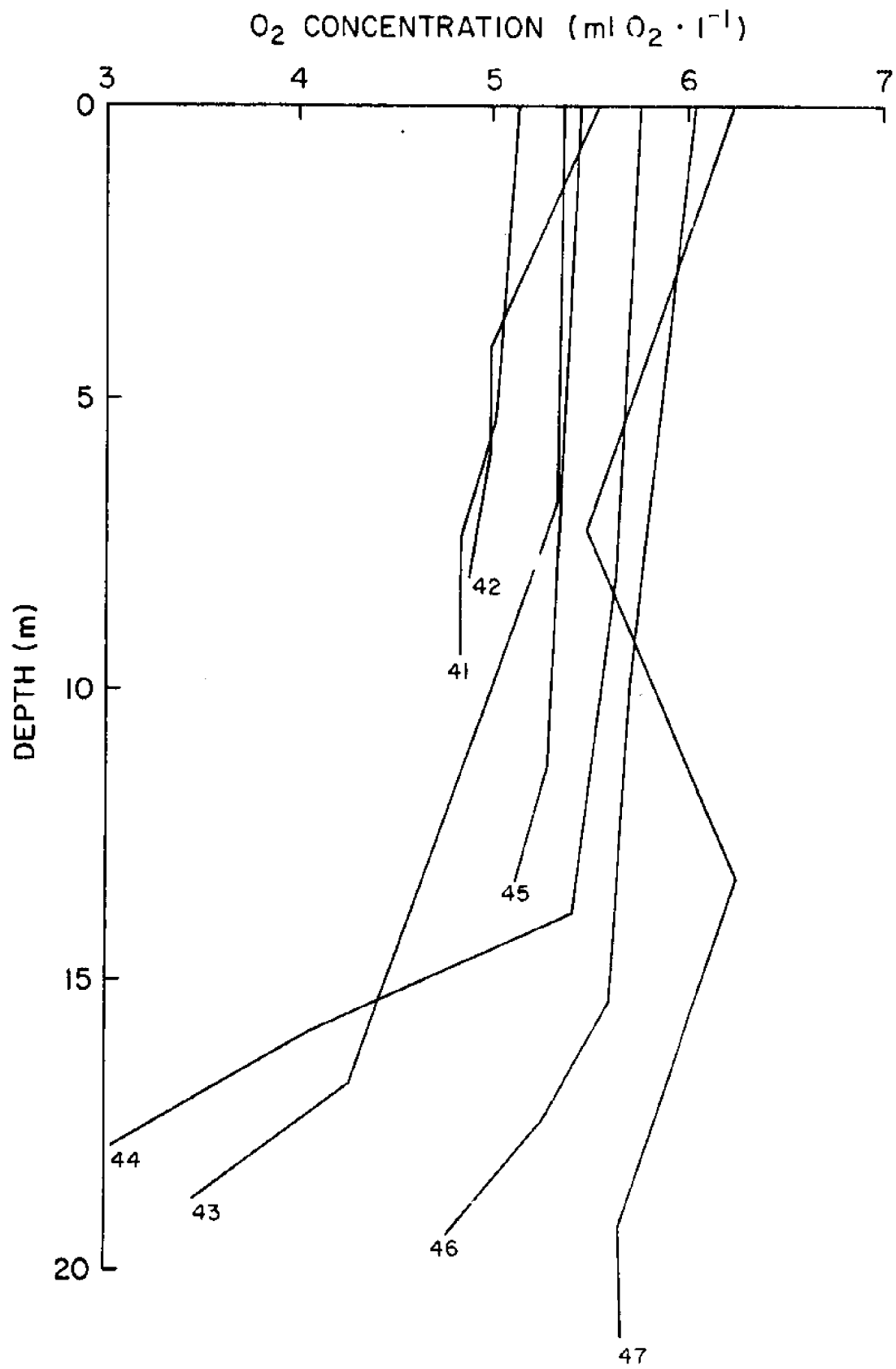
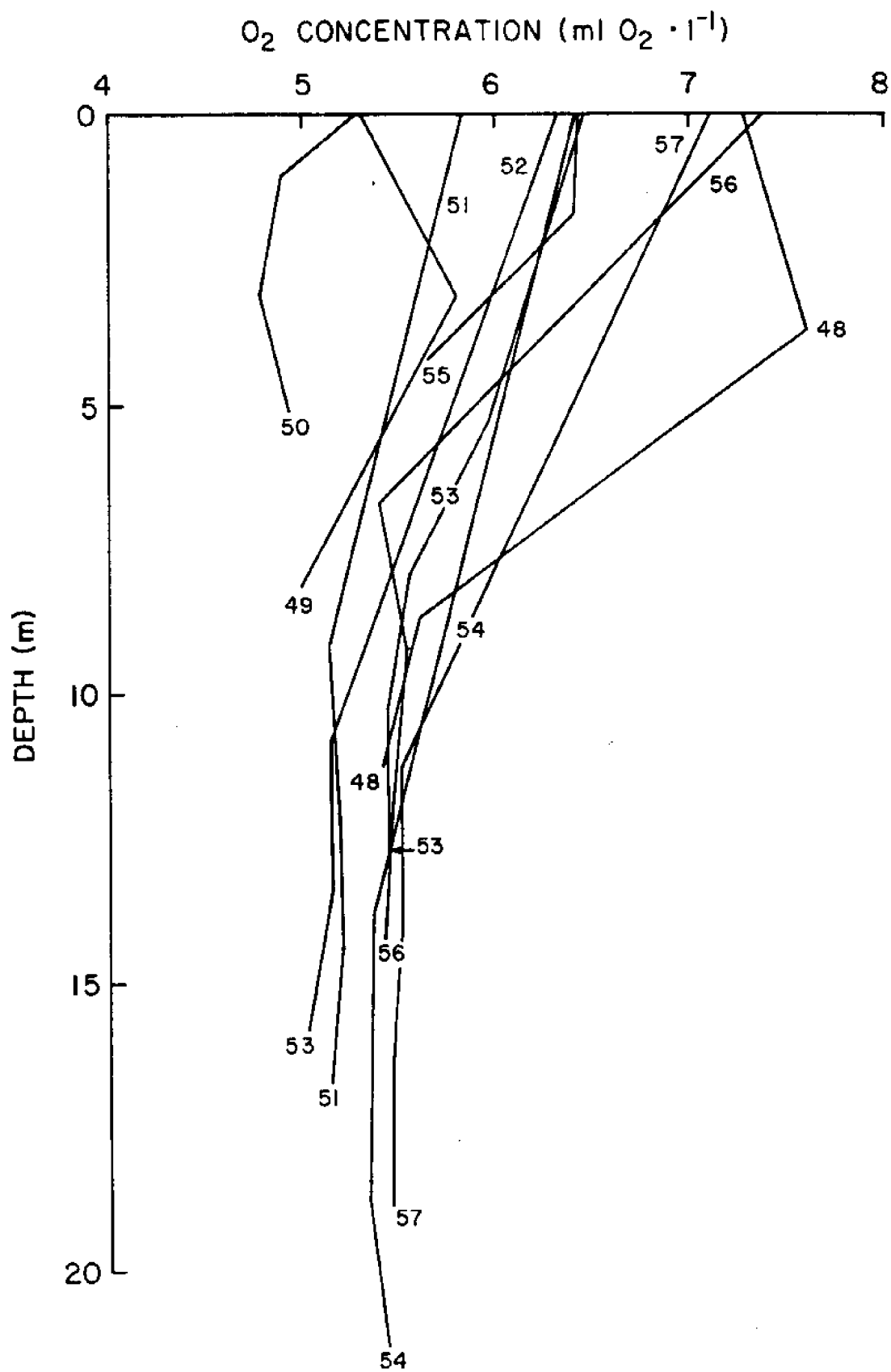


Figure 16

Vertical profile of the dissolved oxygen concentration versus depth
at all stations sampled on 27-VI-78.



the May cruise and located on the West Bank in a hole 20 m deep (Fig. 2-Area "C"), the oxygen concentration dropped from $4.2 \text{ m}\ell \text{ O}_2 \cdot \text{l}^{-1}$ at a depth three meters above the bottom, to $3.4 \text{ m}\ell \text{ O}_2 \cdot \text{l}^{-1}$ one meter above the bottom. At Station 44, also sampled in May and located in the same hole as Station 43, the oxygen concentration dropped from $4.0 \text{ m}\ell \text{ O}_2 \cdot \text{l}^{-1}$ at three meters above the bottom, to $3.0 \text{ m}\ell \text{ O}_2 \cdot \text{l}^{-1}$ one meter above the bottom. And at Station 48, sampled during June and located on the West Bank in a relatively shallow hole 13 meters deep (Fig. 2-Area "A"), the oxygen concentration dropped from $7.6 \text{ m}\ell \text{ O}_2 \cdot \text{l}^{-1}$ at 8.5 meters above the bottom, to $5.6 \text{ m}\ell \text{ O}_2 \cdot \text{l}^{-1}$ 3.5 meters above the bottom.

Vertical profiles of Sigma-T versus depth were plotted from the data obtained on the June and August cruises (Figs. 17 and 18). A well-defined pycnocline was not present at any of the stations sampled during the June and August cruises. However, it is apparent from the graphs that the density of the waters at the East Bank stations differed significantly from that of the waters at the West Bank stations during both cruises.

Summary of results

The data show that fine sediments, with large quantities of organic carbon and sulfide, have accumulated on the seabed in dredged holes on the West Bank. Little or no such accumulations have occurred in dredged areas on the East Bank. Throughout the duration of the study, the oxygen percent saturation of the bottom

Figure 17

Vertical profile of Sigma-T versus depth on 27-VI-78 at East Bank (----) and West Bank(——) stations.

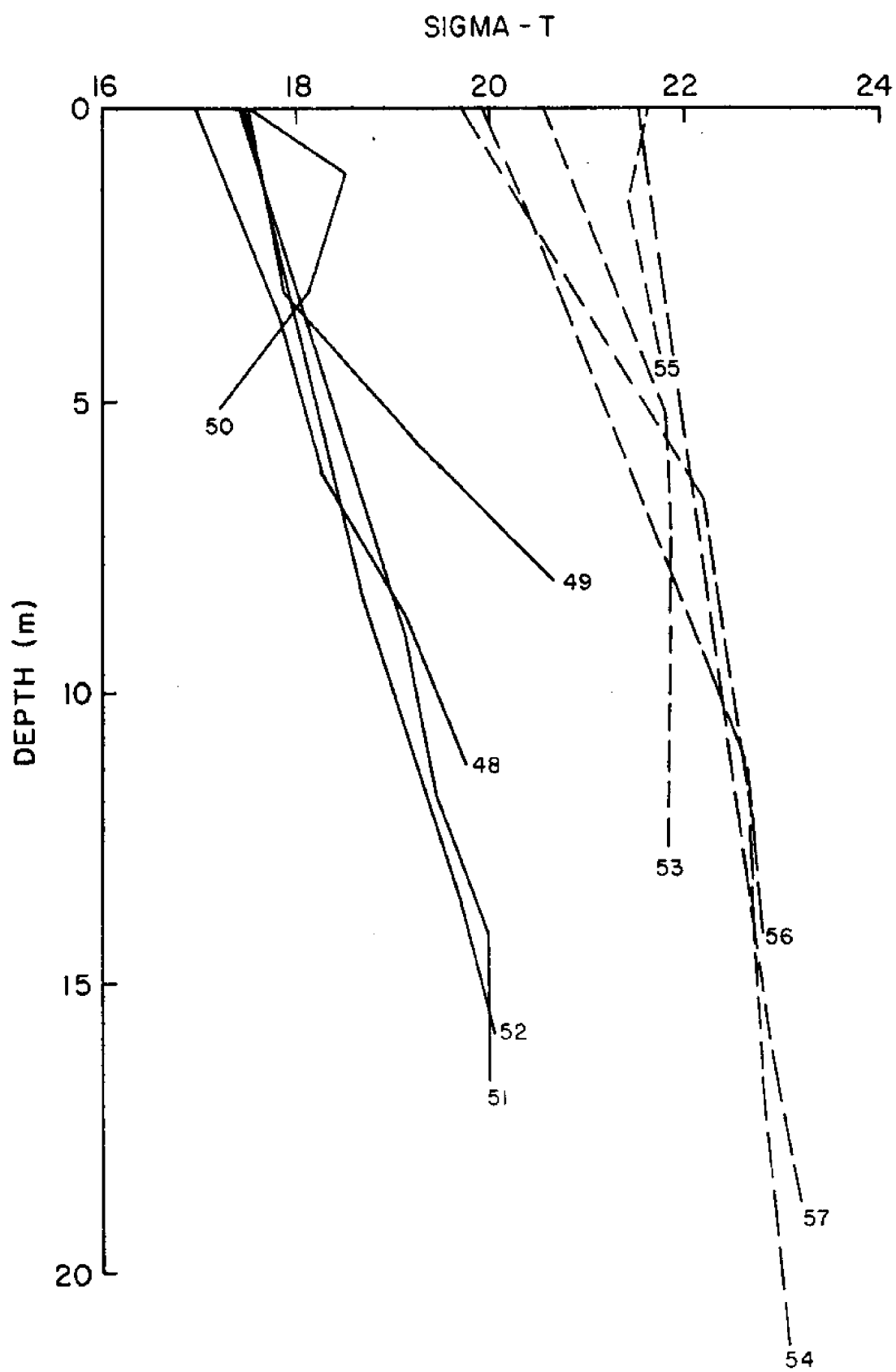
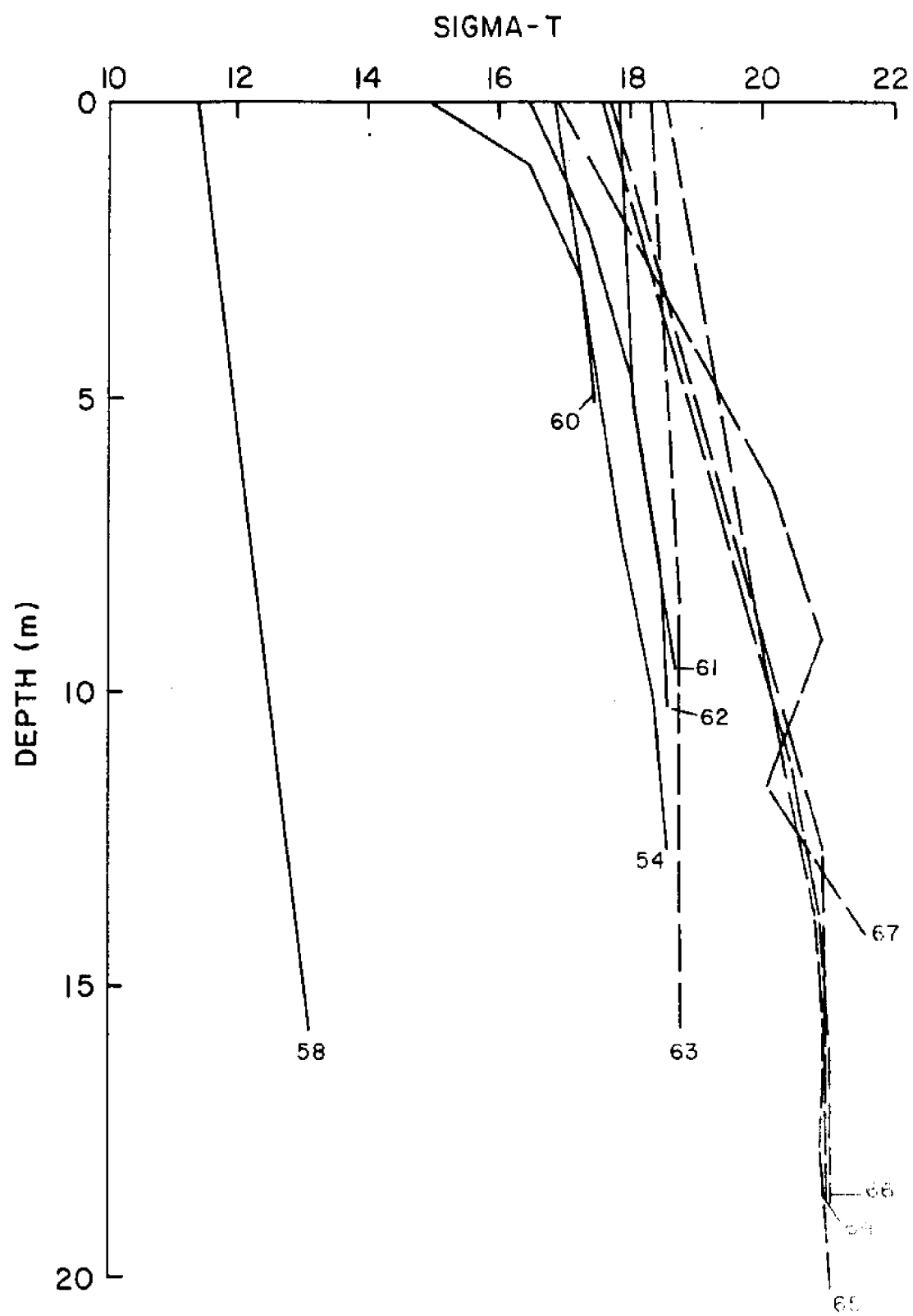


Figure 18

Vertical profile of Sigma-T versus depth on 8-VIII-78 at East Bank (---) and West Bank (—) stations.



waters remained high on both the East and West Banks, with one major exception. The oxygen percent saturation of the bottom waters in the 20 m deep dredged hole on the West Bank (Fig. 2-Area "C") was low during May and August. The highest sulfide, organic carbon, and chemical oxygen demand values were measured in sediments from this same deep hole.

It is also apparent from the data that there are two water types in the Lower Bay (see Fig. 17), namely the dense, saline water on the East Bank and the less dense, fresher water on the West Bank. According to data collected by Parker et al. (1976) in the Sandy Hook-Rockaway Point transect (see Fig. 1), the water in the transect is a mixture of primarily two water types. One type is dense, saline New York Bight water, whose net flow is directed into the Lower Bay near the bottom in the Ambrose Channel, and throughout the water column on the Rockaway Point side of the transect. The other water type is less dense, fresher river water (primarily Hudson River), whose net flow is directed out of the Lower Bay in the surface layers on the Sandy Hook side of the transect. Clearly, the dense, saline waters found on the East Bank during the present study resemble the New York Bight waters identified by Parker et al. and the less dense, fresher waters found on the West Bank resemble the river waters identified by Parker et al.

Discussion

The impact of dredged holes on the oxygen demand of the surficial sediments of the Lower Bay was investigated directly by the oxygen consumption experiments carried out onboard ship, and indirectly by analysis of the physical and chemical properties of the surficial sediments and the overlying waters. The results of the sediment oxygen demand experiments are difficult to interpret. The oxygen demand of sediments is affected by a variety of variables, such as oxygen concentration of the overlying waters, temperature, salinity, turbulence, the type of organic matter present in the sediments, compaction and porosity of the sediments, and the size and composition of the benthic community within the sediments. Further, it is difficult to quantify the effect of each variable on oxygen demand because of factor interactions (Pamatmat, 1973). This is, in part, reflected by the data. There was no single strong correlation between the total oxygen demand of the sediment and 1) the organic carbon content of the sediment, 2) the temperature of the bottom water, 3) the oxygen percent saturation of the bottom water, or 4) the stations' location relative to Ambrose Channel, i.e. East or West Bank. There was, however, a correlation between the chemical oxygen demand of the sediment and both the oxygen percent saturation of the bottom water and the sulfide content of the sediment during August (see Figs. 14 and 12, respectively).

A number of measurements of sediment oxygen demand in the New York Bight Apex and elsewhere have been reported in the literature. Hargrave (1973) gave a range of yearly-averaged sediment oxygen demand values for various lakes, bays, and coastal areas of 1-100 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$. Rowe et al. (1975) reported sediment oxygen demand values for Buzzards Bay, Mass. of 10.35 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at a water temperature of 1.6°C, and 41.89 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 16°C. Smith et al. (1974) reported average values of 11.1 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 5°C, and 36.3 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 17°C for the New York Bight Apex. Measurements of sediment oxygen demand made in the Lower Bay during the present study, yielding average values of 20 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 2°C and 40 $\text{mL O}_2 \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ at 20°C, are comparable to the values obtained by Smith et al. in the New York Bight Apex.

Data obtained from analysis of the physical and chemical properties of the sediments and the overlying waters (i.e. organic carbon and sulfide content of the sediments, and temperature, salinity, and dissolved oxygen concentration of the water column) are more conclusive. It is clear that the character of the sediments and physical/chemical properties of the overlying waters of the East Bank is virtually unaffected by the presence of numerous deeply dredged holes in the seabed. Throughout the duration of the study the organic carbon and sulfide content of East Bank sediments remained low and the dissolved oxygen concentration of the overlying waters remained high. In contrast, it is clear that

the character of the sediments and, at certain times, of the overlying waters in dredged areas on the West Bank has been drastically altered by the presence of dredged holes in the seabed. The sediments in the bottom of the three dredged holes on the West Bank were characteristically dark and fine grained, with high levels of organic carbon and sulfide, whereas undisturbed sediments on the West Bank were light colored and coarse grained, with very low levels of organic carbon and sulfide. The dissolved oxygen concentration of the bottom waters on the West Bank was anomalously low during May and August in the deepest dredged hole.

The observed dissolved oxygen concentration of the bottom waters is the net result of a dynamic balance between oxygen consuming processes within the sediment and water column, and physical processes in the water column which supply oxygen to the bottom waters. Variables such as seasonal changes in biological activity within the sediments and water column, changes in bottom topography, and changes in atmospheric processes affecting the degree of vertical mixing in the water column all can shift this dynamic balance.

During the cold winter months, biological and chemical activity within the sediments and water column are at a minimum and winds affecting the degree of vertical mixing in the water column are at a maximum. In the Lower Bay, these factors result in a condition whereby the oxygen consuming processes in the sediment

and water column are at a minimum and the water column is essentially saturated with dissolved oxygen from top to bottom. The data from the February and March cruises did in fact show that the effect of dredged holes on the oxygen demand of the sediments and the oxygen concentration of the overlying waters was non-existent during the winter.

By May, the water temperature had increased by about 10°C, with the weather becoming milder, though still variable. Along with the increase in water temperature and more hours of daylight, biological activity in the sediments and water column increased as well. The data collected during May indicates these changes. The organic carbon and sulfide content of the sediments from dredged areas on the West Bank had become high, indicating increased biological activity in the sediments and water column. The concentration of dissolved oxygen in the bottom waters of the Lower Bay had decreased and become variable from one station location to another. In fact, the dissolved oxygen concentration in the bottom water of the deepest dredged hole on the West Bank had fallen below the minimum level of $3.5 \text{ mL O}_2 \cdot \text{l}^{-1}$, set by the New York State Department of Environmental Conservation (Neuman, 1978). Thus the data from the May cruise clearly demonstrate that dredged holes on the West Bank can have a major impact on the oxygen demand and the oxygen concentration of the overlying waters.

The data from the June cruise show that the dissolved oxygen

concentration in the bottom waters of the deepest hole on the West Bank had actually risen since the May sampling. The combination of a large standing stock of phytoplankton and high concentrations of untreated sewage effluent (resulting in high water column oxygen demand), and a poorly mixed water column could have been responsible for the low concentrations of dissolved oxygen observed in the bottom waters of the deep hole during May. According to Parker et al. (1976), the highest concentrations of Chlorophyll a in the Sandy Hook-Rockaway Point transect occur in the spring, and then decrease into the summer months. If the phytoplankton standing stock in the waters of the West Bank was very large in May, oxygen demand in the water column could have had a considerable effect on the dissolved oxygen concentration of the bottom waters. Segar and Berberian (1976) report that water column oxygen demand accounts for most of the oxygen consumed from the waters of the New York Bight Apex, and photosynthetically produced carbon accounts for most of the water column oxygen demand, particularly in the late spring and early summer.

Data from sewage treatment records indicate that about $60 \text{ m}^3 \cdot \text{sec}^{-1}$ of treated and untreated sewage effluent is discharged into the local waters surrounding the New York City metropolitan area (Duedall et al., 1976). An increase in the volume of untreated sewage effluent discharged into the Lower Bay, which often occurs during periods of heavy spring rains, could also have contributed

to higher water column oxygen demand in May. By June, the standing stock of phytoplankton and the levels of untreated sewage effluent in the waters of the Lower Bay may have decreased to such an extent that water column oxygen demand no longer exerted a strong influence on the oxygen concentration of the bottom waters in the deep hole.

The fact that oxygen levels in the waters on the East Bank remained high compared to those on the West Bank during May is probably due to the fact that East Bank waters have low levels of Chlorophyll a and are well mixed compared to West Bank waters. According to Parker et al. (1976), the New York Bight waters, from which the East Bank waters are derived, have low levels of nutrients and Chlorophyll a compared to the river waters, from which the West Bank waters are derived. Wilson (personal communication) reports that tidal currents on the East Bank are about twice as strong as those on the West Bank. Since the degree of turbulent mixing in the water column of the Lower Bay increases as the magnitude of the tidal currents and/or the water depth decreases, it is clear that East Bank waters would be well mixed compared to West Bank waters.

Results from the August cruise demonstrate that the adverse impact of dredged holes on the oxygen demand of the sediments and the oxygen concentration of the overlying waters is not necessarily restricted to the time of the spring phytoplankton bloom. The data show that, during August, oxygen concentrations in the bottom

waters of the deep hole on the West Bank and decreased to even lower levels than those observed in May. There was a negative correlation ($r = -0.79$) between the chemical oxygen demand of the sediments and the oxygen percent saturation of the bottom waters, with the highest COD values and lowest percent saturation values being measured in the bottom waters of the deep hole on the West Bank. Clearly, the presence of the dredged holes, isolated in the shallow waters of the West Bank, had a considerable effect on the oxygen demand of the sediments and oxygen concentration of the bottom waters during August. Perhaps holes could be dredged on the West Bank without causing major effects if they were situated adjacent to channels so that greater circulation and exchange with the deeper waters of Ambrose Channel would occur.

Conclusions

The effect of dredged holes in the seabed of the Lower Bay on the oxygen demand of the sediments and the resulting oxygen concentration of the overlying waters is variable and highly dependent on the location of the dredged holes.

The lowest dissolved oxygen concentrations were found in a deeply dredged hole on the West Bank during the spring phytoplankton bloom and late summer. There was no effect of deep holes on oxygen concentrations anywhere on the East Bank at any time.

Bottom topography effects on circulation can be an important factor in controlling the dynamic balance between oxygen consuming processes in the sediments and water column, and physical processes in the water column which supply oxygen to the bottom waters.

References

- American Public Health Association. 1971. Standard Methods for the Examination of Water and Wastewater, 13th ed., Washington, D.C., 874 pp.
- Carpenter, J.H. 1965. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. *Limnology and Oceanography* 10: 141-143.
- Duedall, I.W., H.B. O'Connors, R.E. Wilson, and J.H. Parker. 1976. The Lower Bay Complex. MESA New York Bight Atlas Monograph No. 29. New York Sea Grant Institute, Albany, New York, 48 pp.
- Fray, C.T. 1969. Raritan estuary sedimentation study. Final Report (Alpine Geophysical Associates, Inc., N.J.) prepared for Federal Water Pollution Control Administration, Department of Interior, Washington, D.C., 159 pp.
- Gross, M.G. 1972. Geologic aspects of waste solids and marine waste deposits, New York Metropolitan Region. *Geol. Soc. Amer. Bull.* 83: 31613-3176.
- Hargrave, B.T. 1973. Coupling carbon flow through some pelagic and benthic communities. *J. Fish. Res. Bd. Can.* 30: 1317-1326.
- Kastens, K.A., C.T. Fray, and J.R. Schubel. 1978. Environmental Effects of Sand Mining in the Lower Bay of New York Harbor--Phase I. Marine Sciences Research Center Special Report No. 15. State University of New York, Stony Brook, New York, 144 pp.
- Marotta, J. 1977. Personal communication. New York State Office of General Services, Albany, New York.
- Neumann, J. 1978. Personal communication. New York State Department of Environmental Conservation, New York, New York.
- Pamatmat, M.M., R.S. Jones, H. Sanborn, and A. Bhagwat. 1973. Oxidation of organic matter in sediments. *Ecol. Res. Ser.*, EPA-660/3-73/005, U.S. EPA, 105 pp.

- Parker, J.H., I.W. Duedall, H.B. O'Connors, W. Miloski, G. Hulse, and G. Carroll. 1976. Sandy Hook/Rockaway Point Transect Study: Data Report from November 1973 to June 1974. Final Report-Part II. Prepared for Marine Eco-Systems Analysis (MESA), National Oceanic and Atmospheric Administration, Stony Brook, New York, 15 pp.
- Rowe, G.T., C.H. Clifford, K.L. Smith Jr., and L.P. Hamilton. 1975. Nutrient regeneration and its coupling to primary productivity in coastal waters. *Nature* 255: 215-217.
- Schlee, J., and P. Sanko. 1975. Sand and Gravel. MESA New York Bight Atlas Monograph No. 21. New York Sea Grant Institute, Albany, New York, 26 pp.
- Segar, D.A., and G.A. Berberian. 1976. Oxygen depletion in the New York Bight Apex: Causes and consequences. *Soc. Limnol. Oceanogr. Spec. Symp.* 2: 354-369.
- Smith, K.L., Jr., G.T. Rowe, and C.H. Clifford. 1974. Sediment oxygen demand in an upwelling and outwelling area. *Tethys* 6: 223-230.
- Turano, F.J. 1968. The oxygen consumption of selected sediments of Great South Bay and some of its tributary rivers. M.S. Thesis, Adelphi University, Garden City, New York, 26 pp.
- Weiss, R.F. 1970. The solubility of nitrogen, oxygen, and argon in seawater. *Deep-Sea Res.* 17: 721-735.
- Wilson, R.E. 1978. Personal communication. Marine Sciences Research Center, State University of New York, Stony Brook, New York.

Appendix A

Data obtained from the various analyses of sediments and bottom water at each station sampled during the study period.

Sta.	Type	Depth (m)	Date	Sulfide ($\mu\text{g}\cdot\text{g}^{-1}$)	%LOI	Temp. ($^{\circ}\text{C}$)	O_2 Conc. ($\text{mg}\cdot\text{l}^{-1}$)	O_2 %Sat.	Tot. OD ($\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	COD ($\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	BOD ($\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)
15	D/WB	12.2	2/1	—	10.78	2.0	8.00	102.5*	19.75	—	—
17	D/WB	88.5	2/1	—	8.90	2.5	8.03	102.9*	20.61	—	—
28	D/WB	7.6	3/21	112	8.36	5.5	6.98	93.9*	49.90	—	—
29	D/WB	7.6	3/21	164	12.05	5.5	6.48	87.2*	30.15	—	—
30	D/WB	12.2	3/21	78	5.65	5.0	6.98	93.9*	—	60.64	—
41	D/WB	10.4	5/17	62	1.24	15.0	4.83	82.1*	25.64	0	25.64
42	D/WB	9.1	5/17	721	13.21	15.0	4.88	83.0*	34.65	20.10	14.55
43	D/WB	19.8	5/17	552	16.05	15.0	3.46	58.8*	57.52	0	57.52
44	D/WB	18.9	5/17	539	13.28	15.0	3.04	52.0*	—	32.57	—
45	D/WB	14.3	5/17	29	0.91	15.0	5.13	88.4*	39.50	14.21	25.29
43	D/WB	12.2	6/27	493	6.06	16.5	5.42	95.3	89.74	19.75	69.99
49	D/WB	9.1	6/27	543	13.36	15.2	5.01	86.1	46.08	0	46.08
51	D/WB	17.7	6/27	283	—	16.0	5.15	89.9	—	74.50	—
52	D/WB	16.8	6/27	538	7.16	16.3	5.03	87.9	—	59.25	—
58	D/WB	16.8	8/8	649	15.36	21.8	3.16	58.9	—	118.16	—
59	D/WB	13.7	8/8	868	13.29	21.8	3.20	62.6	—	132.36	—
61	D/WB	10.7	8/8	11	0.80	22.0	3.85	75.3	32.22	20.44	9.78
62	D/WB	11.3	8/8	568	11.14	22.0	3.66	71.6	—	106.72	—
19	ND/WB	4.9	2/1	—	1.16	2.5	7.93	101.6*	20.44	—	—
50	ND/WB	6.1	6/27	58	3.31	17.1	4.93	85.8	—	41.23	—
60	ND/WB	6.1	8/8	17	0.52	22.3	3.66	70.9	—	36.04	—

Sta.	Type	Depth (m)	Date	Sulfide ($\mu\text{g}\cdot\text{g}^{-1}$)	%LOI	Temp. ($^{\circ}\text{C}$)	O ₂ Conc. ($\text{mg}\cdot\text{h}^{-1}$)	O ₂ %Sat.	Tot. OD ($\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	COD ($\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)	BOD ($\text{mg}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$)
24	D/EB	13.7	2/1	—	0.36	4.5	7.85	108.2*	—	—	—
26	D/EB	21.3	2/1	—	0.35	4.0	7.94	109.4*	11.26	—	—
34	D/EB	22.9	3/21	24	0.54	5.0	6.98	95.0*	—	23.22	—
46	D/EB	20.4	5/17	831	3.04	12.5	6.04	98.9*	112.38	62.43	49.95
47	D/EB	22.3	5/17	46	1.14	11.5	5.65	92.5*	43.31	1.73	41.58
53	D/EB	13.7	6/27	69	0.78	14.7	5.44	94.4	80.73	0	80.73
54	D/EB	22.3	6/27	60	3.10	12.6	5.44	91.3	49.90	32.92	16.98
56	D/EB	15.2	6/27	40	0.50	13.5	5.43	92.0	—	15.25	—
57	D/EB	19.8	6/27	44	0.72	12.2	5.46	89.7	—	58.81	—
63	D/EB	16.8	8/8	317	7.77	22.7	3.92	78.3	—	71.87	—
64	D/EB	19.8	8/8	30	1.61	20.5	4.20	81.3	—	48.71	—
65	D/EB	21.3	8/8	276	0.80	20.5	4.01	77.6	—	43.31	—
66	D/EB	19.8	8/8	18	0.32	20.5	4.17	80.7	37.77	12.12	25.65
67	D/EB	15.2	8/8	8	0.49	19.6	4.12	78.5	12.47	9.70	2.77
22	ND/EB	7.9	2/1	—	3.54	4.5	7.74	106.6*	31.53	—	—
40	ND/EB	5.5	3/21	16	0.41	6.0	6.99	98.3*	—	14.55	—
55	ND/EB	5.2	6/27	30	0.43	16.1	5.66	102.5	—	60.29	—

WB = West Bank of Ambrose Channel EB = East Bank of Ambrose Channel
D = Dredged ND = Not Dredged

* Estimated from Parker et al. (1976) salinity data

Appendix B

Profile of data obtained from measurements of the dissolved oxygen concentration, temperature, and salinity at various depths in the water column during the May, June, and August cruises.

Sta.	Bottom Depth(m)	Sample Depth(m)	Temp. (°C)	Salinity (PPT)	Sigma-T [†]	O ₂ Conc. (mg·l ⁻¹)	O ₂ Sat. ^{††}
48	12.2	0	19.5	24.5	16.9	7.2	132.1
		3.7	18.3	25.3	17.8	7.6	136.3
		6.2	17.8	25.6	18.2	—	—
		8.7	16.7	26.5	19.1	5.6	99.3
		11.2	16.5	27.2	19.7	5.4	95.3
49	9.1	0	19.5	24.6	17.5	5.3	98.2
		3.1	18.7	25.4	17.8	5.8	105.9
		5.6	18.0	26.9	19.1	5.4	98.1
		8.1	15.2	28.1	20.6	5.0	86.1
50	6.1	0	18.5	24.9	17.5	5.2	96.1
		1.1	18.0	26.1	18.5	4.8	87.9
		3.1	17.3	25.4	18.1	4.7	84.0
		5.1	17.1	24.1	17.2	4.9	85.8
51	17.7	0	18.0	24.6	17.4	5.8	103.8
		9.2	17.3	26.7	19.1	5.1	90.1
		11.7	16.4	26.8	19.4	5.1	90.3
		14.2	16.1	27.4	19.9	5.2	91.0
		16.7	16.0	27.4	20.0	5.1	89.9
52	16.8	0	18.0	24.7	17.4	6.3	112.5
		8.3	17.7	26.2	18.6	5.4	97.4
		10.8	17.0	26.6	19.1	5.1	91.1
		13.3	16.4	27.1	19.6	5.1	89.8
		15.8	16.3	27.5	20.0	5.0	87.9
53	13.7	0	17.2	28.5	20.5	6.4	115.9
		5.2	16.7	30.0	21.8	5.9	108.3
		7.7	16.0	29.9	21.8	5.5	99.3
		10.2	15.7	29.8	21.8	5.4	96.6
		12.7	14.7	29.5	21.8	5.4	94.4

Sta.	Bottom Depth(m)	Sample Depth(m)	Temp.	Salinity (PPT)	Sigma-T ⁺	O ₂ Conc. (mL·l ⁻¹)	O ₂ Sat. ⁺
54	22.3	0	15.8	29.4	21.5	6.4	113.7
		13.8	14.0	30.4	22.7	5.3	92.0
		16.3	13.9	30.5	22.8	5.3	91.6
		18.8	13.5	30.6	22.9	5.3	91.6
		21.3	12.6	30.6	23.0	5.4	91.3
55	5.2	0	16.1	29.6	21.6	6.4	113.9
		1.7	16.8	29.5	21.4	6.4	115.8
		4.2	16.8	30.0	21.7	5.6	102.5
56	15.2	0	17.1	27.3	19.7	7.3	131.7
		6.7	15.4	30.1	22.2	5.4	94.1
		9.2	15.0	30.3	22.4	5.5	96.8
		11.7	14.0	30.4	22.6	5.4	93.7
		14.2	13.5	30.4	22.8	5.4	92.0
57	19.8	0	16.0	27.3	19.9	7.1	124.2
		11.3	14.2	30.4	22.6	5.5	94.4
		13.8	14.3	30.5	22.7	5.5	94.5
		16.3	13.5	30.6	22.9	5.4	92.4
		18.8	12.2	30.6	23.2	5.4	89.7
58	16.8	0	22.3	18.0	11.4	—	—
		8.3	22.1	19.1	12.2	—	—
		10.8	22.0	19.5	12.5	—	—
		13.3	21.9	19.7	12.7	—	—
		15.8	21.8	20.0	13.0	3.1	58.9
59	13.7	0	22.4	25.3	16.8	—	—
		5.3	22.2	26.2	17.5	—	—
		7.8	22.1	26.6	17.9	—	—
		10.2	21.9	27.1	18.3	—	—
		12.7	21.8	27.3	18.5	3.2	62.6

Sta.	Bottom Depth(m)	Sample Depth(m)	Temp. (°C)	Salinity (PPT)	Sigma-T ⁺	O ₂ Conc. (mg·l ⁻¹)	O ₂ % Sat. ⁺⁺
60	6.1	0	23.9	23.3	14.9	—	—
		1.1	22.6	24.9	16.4	—	—
		3.1	22.3	25.8	17.2	—	—
		5.1	22.3	26.0	17.4	3.6	70.9
61	10.7	0	22.7	24.9	16.4	—	—
		2.2	22.4	26.0	17.3	—	—
		4.7	22.2	26.8	18.0	—	—
		7.2	22.1	27.1	18.3	—	—
		9.7	22.0	27.6	18.6	3.8	75.3
62	11.3	0	22.2	26.2	17.8	—	—
		2.8	22.2	26.7	17.9	—	—
		5.3	22.2	26.9	18.0	—	—
		7.8	22.0	27.3	18.4	—	—
		10.3	22.0	27.4	18.5	3.6	71.6
63	16.8	0	22.4	27.3	18.3	—	—
		8.3	22.7	27.9	18.7	—	—
		10.8	22.7	27.9	18.7	—	—
		13.3	22.7	27.9	18.7	—	—
		15.8	22.7	27.9	18.7	3.9	78.3
64	19.8	0	22.9	27.8	18.5	—	—
		11.3	21.3	29.5	20.3	—	—
		13.8	20.7	29.9	20.7	—	—
		16.3	20.5	30.1	20.9	—	—
		18.8	20.5	30.1	20.9	4.2	81.3
65	21.3	0	23.4	26.8	17.6	—	—
		12.8	20.7	30.1	20.9	—	—
		15.3	20.7	30.1	20.9	—	—
		17.8	20.7	30.0	20.8	—	—
		20.3	20.5	30.1	21.0	4.0	77.6

Sta.	Bottom Depth(m)	Sample Depth(m)	Temp. (°C)	Salinity (PPT)	Sigma-T [†]	O ₂ Conc. (mL · l ⁻¹)	O ₂ % Sat. ^{††}
66	19.8	0	23.4	26.6	17.5	—	—
		11.3	21.3	29.7	20.4	—	—
		13.8	20.7	30.0	20.8	—	—
		16.3	20.5	30.1	21.0	—	—
		18.8	20.5	30.1	21.0	4.1	80.7
67	15.2	0	24.2	26.0	16.8	—	—
		6.7	21.5	29.5	20.2	—	—
		9.2	20.6	30.1	20.9	—	—
		11.7	20.4	30.2	21.0	—	—
		14.2	19.6	30.6	21.5	4.1	78.5

[†] Sigma-T was computed from Tables for Seawater Density, U.S. Navy Hydrographic Office, 152.

^{††} Oxygen percent saturation was computed from the equations of Weiss (1970).

